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ABSTRACT

This educator guide for grades K-4 and 5-8 presents the basic science of aeronautics by emphasizing hands-on involvement, prediction, data collections and interpretation, teamwork, and problem solving. Activities include: (1) Finding the Center of Gravity Using Rulers; (2) Finding the Center of Gravity Using Plumb Lines; (3) Changing the Center of Gravity Using Moment Arms; (4) Jet Propulsion; (5) Vectoring; (6) Center of Gravity, Pitch, Yaw; and (7) Fuel Efficiency. (MVL)

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Exploring the Extreme

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High Performance Learning Activities in Mathematics, Science and Technology

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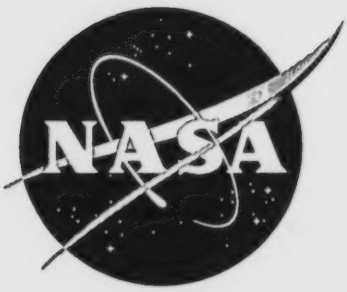
Exploring the Extreme

High Performance Learning Activities in Science, Mathematics and Technology Education



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NASA Dryden Flight Research Center

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How To Use This Guide

Controlled flight by humans was attempted early in the last millenium but only mastered for heavier-than-air vehicles in the last century. Tremendous progress was achieved in the twentieth century in aircraft performance and mission capability through research in flight controls, aircraft stability, and propulsion. Modern technology was applied to aeronautics in the last century as aggressively as in other fields, such as medicine, communications, and geosciences. So many advances have been made, that today the demands of performance and maneuverability for many advanced aircraft designs require extensive use of computers to aid the pilot in controlling flight.

With some simple inexpensive materials, you can mount an exciting and productive unit for children that incorporates science, mathematics, and technology education. The many activities contained in this teaching guide emphasize hands-on involvement, prediction, data collection and interpretation, teamwork, and problem solving. The guide also contains background information about aeronautical research that can help students learn how airplanes fly.

Following the background sections are a series of activities that demonstrate the basic science of aeronautics while offering challenging tasks in design. Each activity employs basic and inexpensive materials. In each activity you will find construction diagrams, material and tools lists, and instructions. A brief background section within each activity elaborates on the concepts covered and points back to the introductory material in this guide. Also included is information about where the activity applies to science and mathematics standards, assessment ideas, and extensions.

Because many of the activities and demonstrations apply to more than one subject area, a matrix chart identifies

opportunities for extended learning experiences. The chart indicates these subject areas by activity title. In addition, many of the student activities encourage student problem-solving and cooperative learning. The length of time involved for each activity varies according to its degree of difficulty and the development level of the students.

Finally, the guide concludes with a glossary of terms, suggested reading list, NASA educational resources including electronic resources, and an evaluation questionnaire. We would appreciate your assistance in improving this guide in future editions by completing the questionnaire and making suggestions for changes and additions.

A Note on Measurement

In developing this guide, metric units of measurement were employed. In a number of instances, English units are used or shown along with metric units because of the standard practices in the aviation community, such as altimeters displaying feet instead of meters.

F-15 ACTIVE (Advanced Control Technology for Integrated VEhicles) Research Program History and Technology

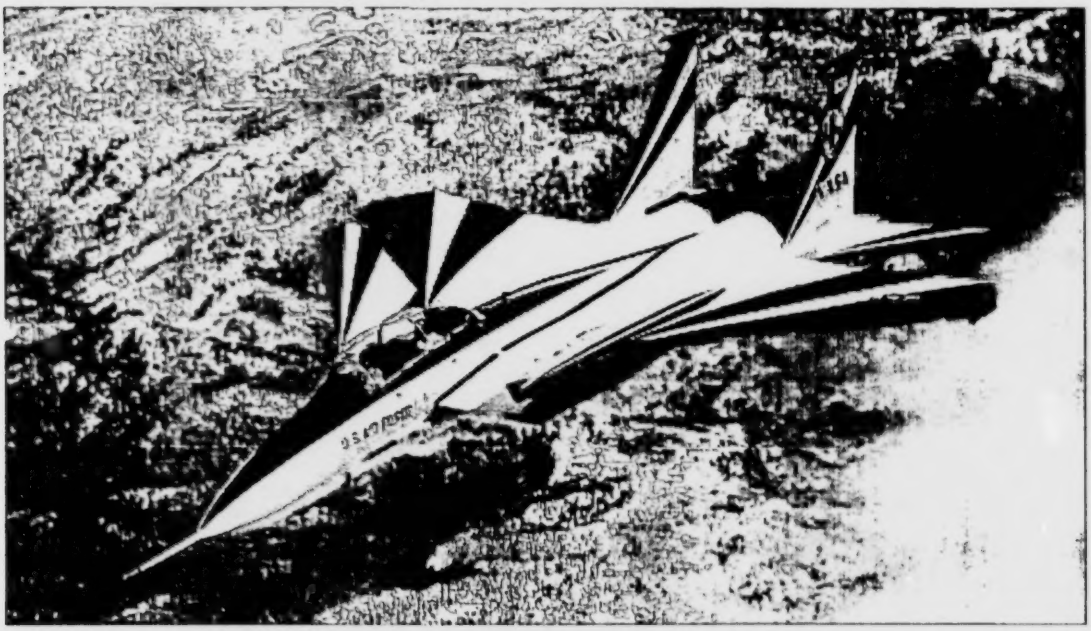

Figure 1-1
F-15 ACTIVE

This highly modified F-15 fighter was just one of the aircraft used by NASA to explore the extreme limits of aerospace technology. The aircraft was built in 1972, and modified for the U.S. Air Force's Short Takeoff and Landing Maneuvering Technology Demonstrator (STOL/MTD) flight research program which lasted from the mid-1980s until 1991. Beginning in 1993 it was involved in a NASA, U.S. Air Force, and private industry flight research program called Advanced Control Technology for Integrated Vehicles (ACTIVE). The F-15 ACTIVE program concluded in 1999. Since then the aircraft has been used as a testbed for "intelligent flight control systems" that enable a pilot to maintain control and safely land an aircraft that has suffered a major systems failure or combat damage.

History and Technical Discussion

Pilots can maneuver an airplane about each of its three **axes,** producing motions called **pitch**, **roll**, and **yaw** (figure 1-2). Pilots steer the airplane's flight path as desired by controlling pitch, roll, and yaw with a control wheel (or stick) and foot pedals located in the cockpit. These cockpit controls are in turn connected to movable panels, called **flight control surfaces**, attached to the airplane's structure. These surfaces are named the **elevator**, **ailerons**, and **rudder** (figure 1-3). The elevator produces pitch up or down when the pilot moves the control stick backward or forward. Ailerons cause the airplane to roll right or left corresponding to right or left movement of the control stick. The rudder produces right or left yaw corresponding to right or left rudder pedal movement.

A recent flight control design incorporated in the F-15 ACTIVE (figure 1-1) is the use of **thrust vectoring** to also produce pitch, roll, and yaw. Here, the jet engine's exhaust **nozzle**

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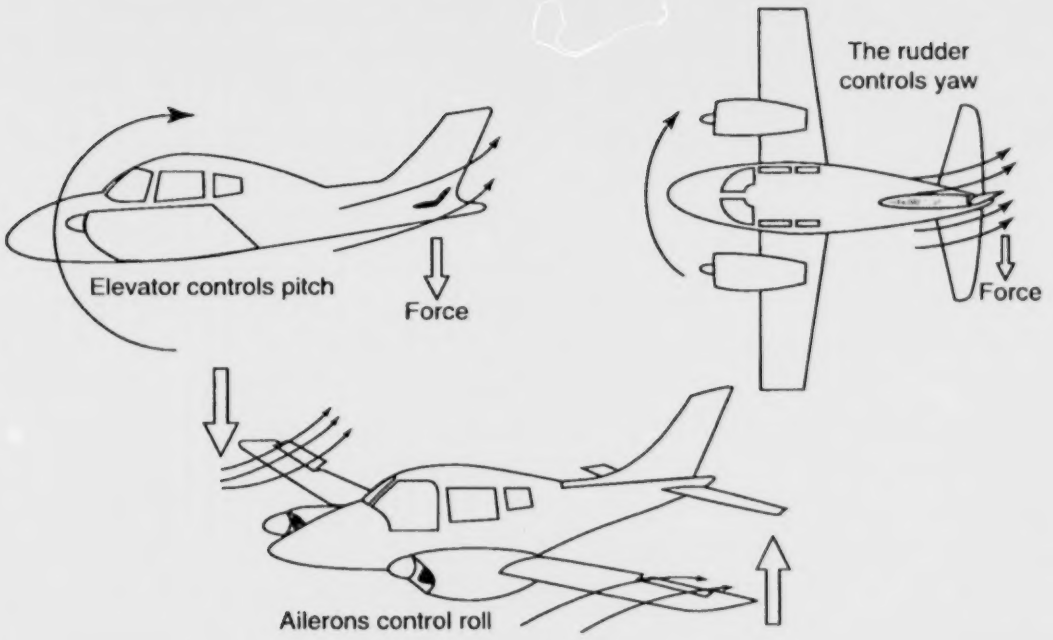

Figure 1-2
Three axes producing motions called pitch, roll, and yaw.

Figure 1-3
Supermarine Spitfire

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moves as well as the flight control surfaces when the pilot moves the control stick. This movable nozzle deflects the exhaust stream to produce the desired motion. Thrust vectoring causing a nose-up pitching motion is illustrated in figure 1-4. Deflecting the exhaust stream upward causes a reaction force that moves the tail down (and nose up), complementing the usual nose-up motion due to elevator deflection.

"Vectoring" for jets simply means pointing the engine exhaust in various directions (direction + magnitude = vector) to change the direction of the aircraft's flight path. You may have driven a small boat by pointing an outboard motor to steer the boat; it's much the same idea.

Here is a more formal definition of thrust vectoring: the manipulation of jet engine exhaust such that the resultant reaction forces augment, or in some cases, replace, those forces normally generated by the aerodynamic control surfaces.

Flight Control Design

Mechanical Flight Controls

From the Wright Flyer through most World War II airplane designs, the pilot's stick and rudder pedals were connected to the flight control surfaces with steel cables. Thus, these designs are often called "manual" or "mechanical" flight control systems.

In such a design, pressure of the airflow over the airplane's flight control surfaces resists movement of the cockpit control stick. Since faster speeds produce higher air pressures, it becomes progressively harder for the pilot to physically move the stick as **airspeed** increases.

Hydraulic Flight Controls

To allow the pilot to be able to move the control stick at very high speeds, hydraulically powered flight control systems were introduced. Here, a hydraulic actuator moves the control surface and essentially multiplies any force the pilot applies to the stick many times over as it positions the control surface. While permitting supersonic flight, hydraulic flight control systems posed new problems for pilots in controlling these airplanes. It was often difficult for the pilot to predict how much stick force was necessary to produce the desired response. Control forces, which were natural and predictable in a mechanical flight control aircraft, were reproduced artificially in the hydraulic aircraft. Optimizing the various devices involved over the entire **flight envelope** proved difficult, and it was not uncommon for pilots of these highly

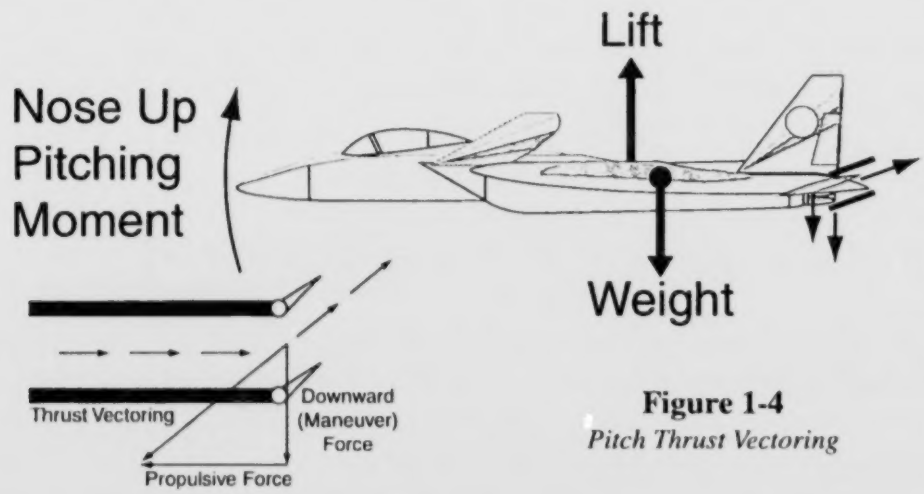


Figure 1-4
Pitch Thrust Vectoring

maneuverable aircraft to lose control. Additionally, failures of the hydraulic system, such as ruptured fluid supply lines or overheated pumps, plagued these designs.

Fly-By-Wire Flight Controls

In the 1960s, designers turned to electronics and computer technologies to overcome many of the problems associated with hydraulically powered flight controls. Hydraulic actuators were still necessary, but fly-by-wire meant that the pilot's control stick movements were now transmitted electronically to the actuators. Also, a computer allowing much-improved flight path control precision could control the airplane's response. NASA research was the driving force for the successful development of fly-by-wire aircraft.

The NASA Digital Fly-By-Wire (DFBW for short) research aircraft, a modified U.S. Navy F-8 Crusader, was one of the most significant research programs in NASA history. On May 25, 1972, NASA 802 became the first aircraft to fly completely dependent upon an electronic flight control system (no mechanical backup). It used a computer from the Apollo spacecraft to operate the flight controls. The DFBW F-8 validated the concepts of the fly-by-wire flight control systems now used on nearly all modern high-performance aircraft, military and civilian transports, and the Space Shuttle flight control system.[1] The F-15 ACTIVE research aircraft is equipped with a digital fly-by-wire flight control system.

Digital flight-control systems were able to incorporate "multi-mode" flight control laws with different modes, each optimized to enhance maneuverability and controllability for a particular phase of flight. Earlier mechanical or electronic flight control systems could be optimized for only one particular set of flight conditions, such as supersonic flight, weapons carriage, or perhaps takeoff and landing. But the DFBW designs could "flip a switch," giving a separate set of software **control laws** for each flight phase the aircraft would encounter. Thus, a design might have a takeoff and landing mode with its set of control laws, a cruise mode with a different set of control laws, a weapons delivery mode, supersonic mode, and so on. Development of thrust vectoring control laws is part of the F-15 ACTIVE research.

Thrust Vectoring and Fly-By-Wire Combined

Thrust vectoring produces greater agility and maneuverability, especially at slow airspeeds and at a high **angle-of-attack** (relationship between the aircraft's wings and actual flight path). Whereas aerodynamic control surfaces lose their ability to produce pitch, roll, or yaw at slow airspeeds, thrust vectoring still remains quite effective. This is because the pressure of engine thrust against the nozzles stays relatively constant while the air pressure on control surfaces goes down exponentially as airspeed decreases. In fact, aerodynamic surfaces can lose effectiveness altogether if the angle-of-attack gets too high (called a **stall**).

Fly-by-wire computers do the job of properly blending the amount of control surface deflection and thrust vectoring needed. This allows the pilot to simply move the stick in the desired direction, so that flying a thrust vectored airplane is no more difficult, or different, than flying a conventional airplane.

Other design benefits include less **drag** from **elevator/stabilator** deflections for **balance (trim drag)**; that is, the use of thrust vectoring instead of control surface deflection for balance requirements. This in turn results in better fuel efficiency (due to less trim drag) and reduced operating costs. Thrust vectoring makes possible new, more aerodynamically efficient configurations, such as tailless aircraft

with reduced weight due to replacement of control surface area. Safety can be improved by preventing stalls and loss of control and with reconfigurable flight controls using thrust vectoring to replace a malfunctioning control surface. Finally, slower landing speeds are possible, allowing shorter, less expensive runways to be used.

Related Programs and Research

Harrier "Jump Jet" Operational Experience

One of the first operational aircraft to use thrust vectoring was the Harrier, flown by the British Royal Air Force, British Royal Navy, and the U.S. Marines. The first flight of the prototype, called the Kestrel, was in 1960. The Harrier uses four movable engine exhaust nozzles that may be rotated downward, as illustrated in figure 1-5, for vertical takeoff or landing. Its thrust vectoring capability was not designed for in-flight maneuvers other than takeoff and landing.

MATV, HARV, and X-31

NASA research explored thrust vectoring at extremely high angle-of-attack on the High Alpha (angle-of-attack) Research Vehicle (HARV), a modified F-18. The F-16 Multi-Axis Thrust Vectoring (MATV) research program made significant contributions to understanding thrust vectoring design requirements and agility benefits. The X-31 research aircraft is continuing to help NASA learn about the benefits of thrust vectoring (figure 1-6). Whereas a small airplane like those you might see at the local airport might stall and lose control at about 15 degrees angle-of-attack, the X-31 has demonstrated controlled flight to 70 degrees angle-of-attack as well as flight with the vertical stabilizer and rudder completely removed (figure 1-7).

F-15 S/MTD

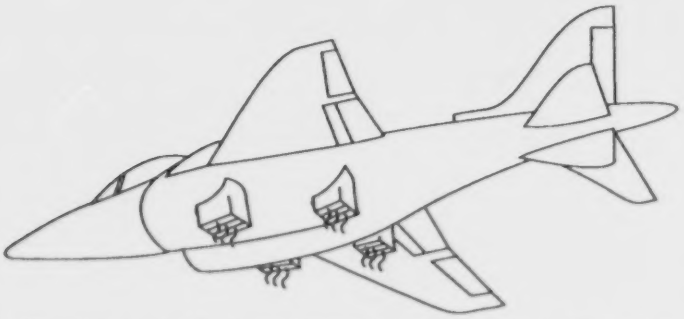
The F-15 S/MTD (STOL [Short Take Off and Landing]/Maneuvering Technology Demonstrator) testing focused on short takeoffs and landings as well as on enhancing pitch maneuvering capabilities. The first flight with the vectoring nozzles was in May 1989 and flight testing lasted until late 1991. The program demonstrated significantly shorter runway requirements of about 50 percent over production F-15s, inflight use of thrust reversing for deceleration improvement, and enhanced pitching moments with pitch thrust vectoring.[2] The ACTIVE effort evolved from the S/MTD program at the NASA Dryden Flight Research Center.

F-15 ACTIVE Research Program

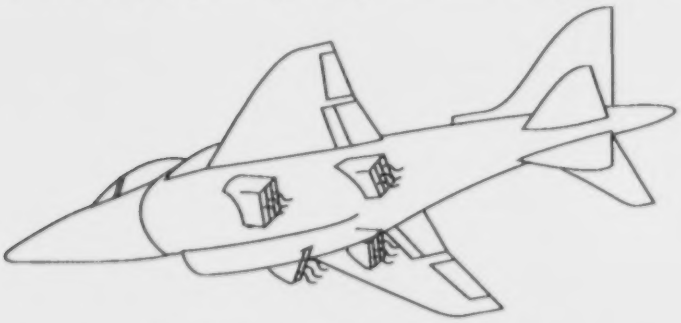
The F-15 ACTIVE research program combined the latest in fly-by-wire flight control system and three-dimensional (3-D) thrust vectoring technologies. While previous programs demonstrated one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) vectoring during very slow speed, high angle-of-attack conditions, the F-15 ACTIVE was used to study the utility of thrust vectoring over a broader spectrum of flight conditions. The overall goal of the F-15 ACTIVE test program was to expand the flight envelope in which useful thrust vectoring is available to enhance aircraft performance, maneuverability, and controllability using production-representative (those that could be mass-produced economically) thrust vectoring nozzles.[3]

Aircraft Description

The test aircraft was a USAF F-15B (two-seat version), tail number 71-0290, and became NASA 837. This aircraft has been through many modifications over the years for various test programs so it is quite different from production F-15 aircraft. It was selected for the ACTIVE research because of the flexibility of its unique, digital, fly-by-wire, integrated flight control and propulsion system. The cockpit



Harrier nozzles pointing down for vertical aircraft movement



Harrier nozzles rotated aft for cruise

Figure 1-5

Figure 1-6

F-18 HARV, X-31, and F-16 MATV (left to right)

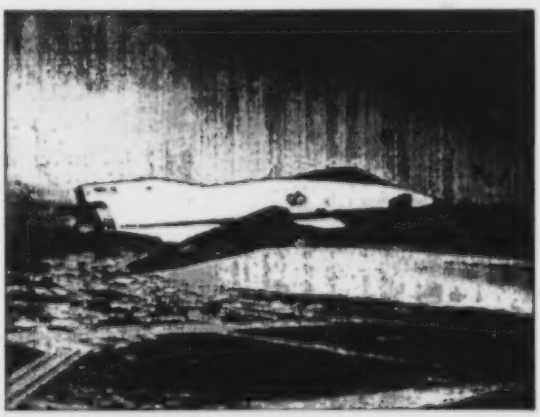


Figure 1-7

NASA X-31 in a tailless configuration

closely resembles the F-15E "glass" cockpits with electronic flight instrument displays and a wide field-of-view Head Up Display. Externally, **canard** flight control surfaces (actually modified F-18 stabilators) were added on the left and right upper inlet areas forward of the wing.

Most importantly, this aircraft had special nozzles for each of the two Pratt & Whitney **afterburning** engines that can vector up to 20 degrees in any direction from the thrust centerline.[3]

F-15 ACTIVE Statistics

Maximum Altitude: 65,000 ft
Maximum Speed: Mach 2.0+
Weight: 54,000 lbs at takeoff,
46,000 lbs empty
Fuel Capacity: 11,520 lbs
(approximately 1,700 gal)
Engines: Two Pratt & Whitney F100–PW-229 thrust vectoring turbofan jet engines
Engine Nozzles: Pratt & Whitney Pitch/Yaw Balance Beam Nozzles (PYBBN)
Wingspan: 42.10 ft
Length: 63.9 ft (excluding the nose boom)
Height: 18.8 ft
Horizontal Tail (stabilator) Span: 28.2 ft
Canard Span: 25.6 ft

The F-15 ACTIVE had nine control effectors: left canard, right canard, left aileron, right aileron, left stabilizer, right stabilizer, rudder (two surfaces counted as one effector since they move together), pitch nozzle, and yaw nozzle (figure 1-8). Flight demonstration of a computer program that can optimize these nine effector movements as well as engine thrust to maximize performance factors, such as range, is a major objective of ACTIVE. The cockpit controls for some these effectors are shown in figure 1-9.

ACTIVE Testing

F-15 ACTIVE testing was a joint program conducted by NASA, USAF, Boeing Phantom Works (formerly McDonnell Douglas Aerospace Phantom Works), and Pratt & Whitney. As mentioned, the F-15 ACTIVE research used the very same aircraft as the F-15 S/MTD program. The major change to the F-15B test aircraft was the installation of Pratt & Whitney Pitch/Yaw Balance Beam Nozzles (PYBBN for short). PYBBN design has matured to the point where they could be used in a production series of aircraft.[3] The first order of business was to "clear the envelope" to make sure the nozzles would operate as expected throughout the F-15 ACTIVE's flight envelope (figure 1-10) without causing any unwanted side effects or engine problems. Next was to find out how well the nozzles actually vectored engine exhaust and determine whether the additional loads imparted to the tail end of the aircraft were acceptable. Initial testing also evaluated improvements in aircraft performance due to thrust vectoring.

F-15 ACTIVE flight testing commenced on February 14, 1996, with the first vectoring flight, at 20,000 feet and Mach 0.6, less than one month later, on March 7. The first supersonic pitch vectoring was on April 24, taking ACTIVE to Mach 1.2 at 30,000 feet. This was followed by a "world first" supersonic yaw vectoring at Mach 1.6 and 45,000 feet, on June 13. By November, thrust vectoring had been performed as fast as Mach 1.95 at 45,000 feet and as slow as 200 knots at 30,000 feet with angle-of-attack at 30 degrees.[4] Testing demonstrated successful operation of the PYBBN nozzles and problem-free engine operation.

Additional testing was done to evaluate the impact of the vectored exhaust plume on

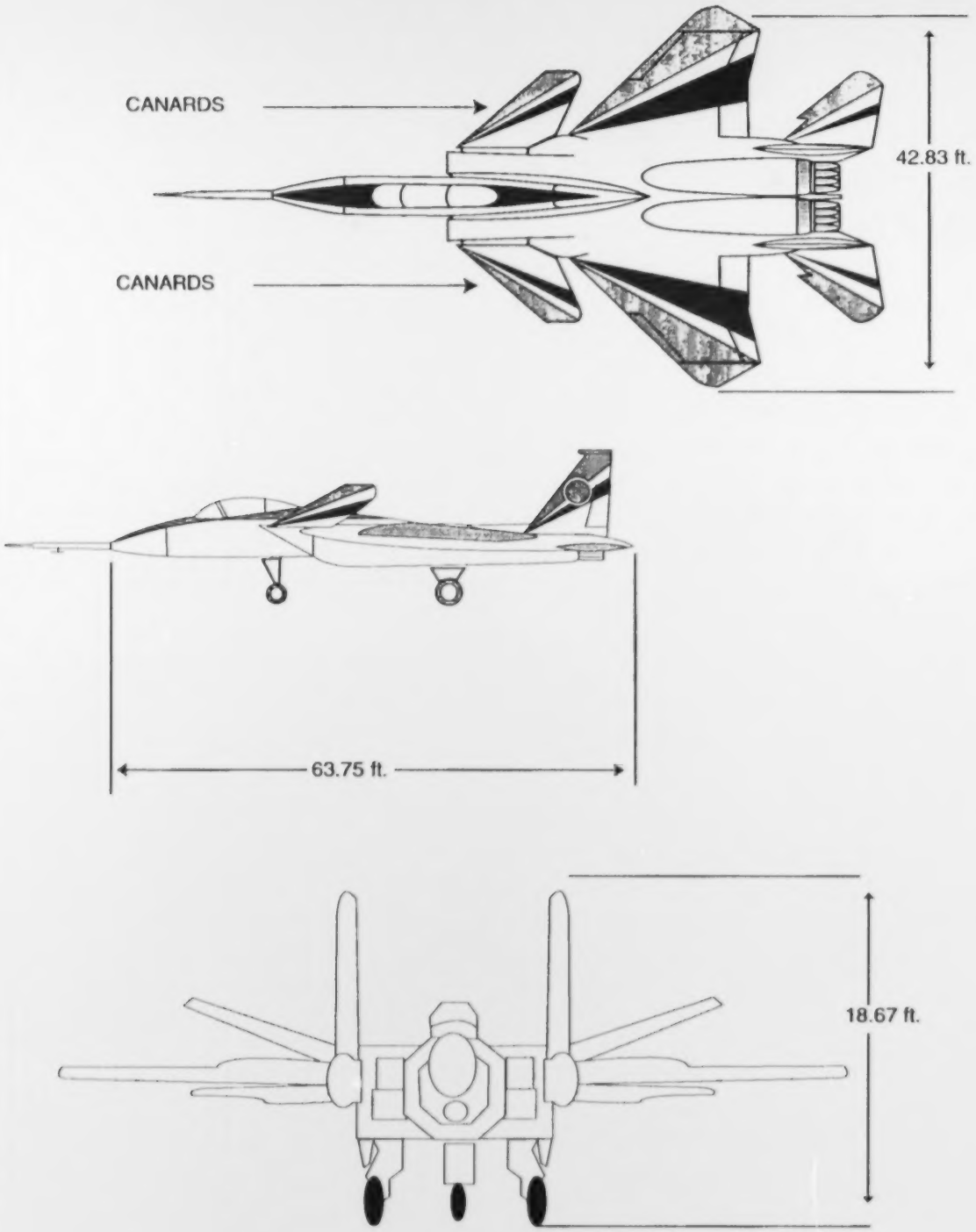


Figure 1-8

Control Effectors of F-15 ACTIVE

Figure 1-9
F-15 ACTIVE cockpit

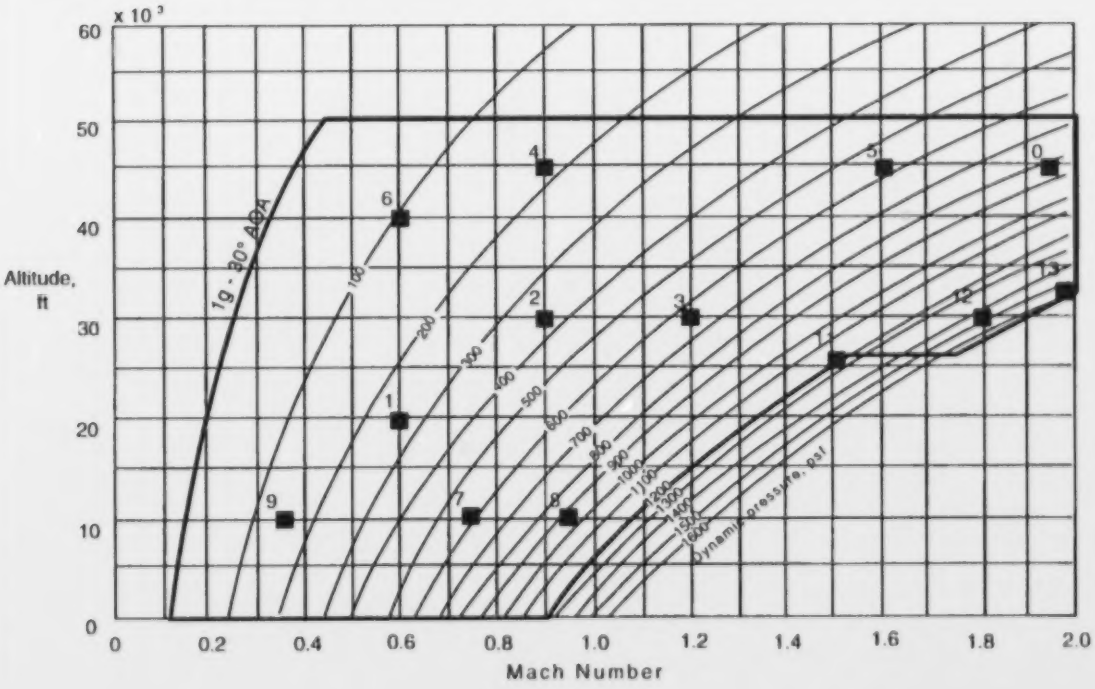


Figure 1-10

F-15 ACTIVE flight envelope showing the 13 "test points" where tests were completed to clear the envelope. Initial flight test results demonstrated successful operations of the PYBBN nozzles up to Mach 2.0 in vectored flight. Engine operation was problem free during vectoring, maneuvering, and throttle movement.

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aircraft response and stability. These jet interaction effects were important to define for future aircraft designs such as the Joint Strike Fighter program. Additional tests proved that the PYBBN nozzles did not impact engine operability and that the Pratt & Whitney design was well suited for future ACTIVE research objectives.[4]

Included in the research experiments was an advanced fly-by-wire flight control system called "Intelligent Flight Control." This system allows the aircraft to automatically adapt to unforeseen changes due to failures or battle damage to flight controls by directing the remaining control effectors to compensate for the malfunctioning ones. This could allow future aircraft to safely land after sustaining major damage or system failures.

This concludes the introduction to the F-15 ACTIVE research program. You should now have an appreciation of aerodynamic design evolution, thrust vectoring concepts, fly-by-wire flight controls, and integration of these technologies as they have influenced the configuration of the F-15 ACTIVE aircraft.

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Activity Matrices

Curriculum and Evaluation Standards for School Mathematics
National Council of Teachers of Mathematics in 1989

	Finding the Center of Gravity Using Rulers	*Finding the Center of Gravity Using Plumb Lines*	*Changing the Center of Gravity with Moment Arms*	*Jet Propulsion*	*Vectoring*	*Center of Gravity, Pitch, Yaw*	*Fuel Efficiency*
Mathematics as Problem Solving	X	X	X		X		
Mathematics as Communication	X	X	X	X			X
Mathematics as Reasoning	X	X	X	X	X		X
Mathematical Connection				X		X	
Computation and Estimation			X			X	X
Algebra							
Geometry					X		
Measurement	X	X	X			X	

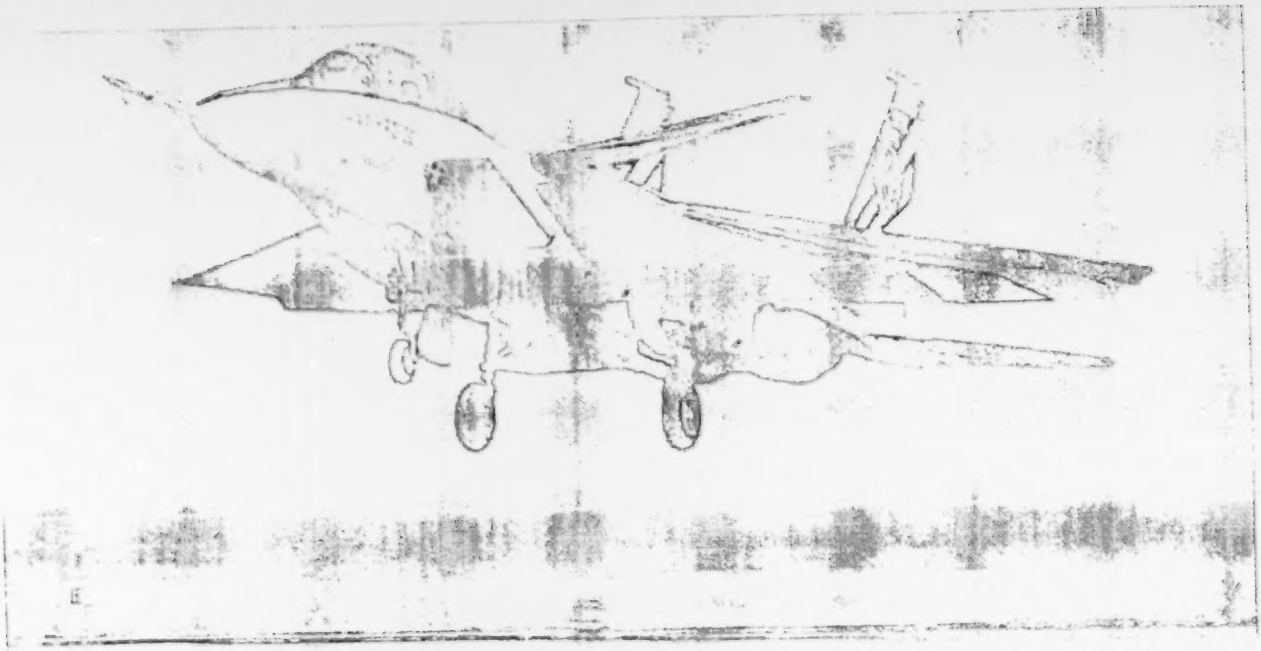
National Science Education Standards

National Research Council 1996 Grades 4-12

	Finding the Center of Gravity Using Rulers	*Finding the Center of Gravity Using Plumb Lines*	*Changing the Center of Gravity with Moment Arms*	*Jet Propulsion*	*Vectoring*	*Center of Gravity, Pitch, Yaw*	*Fuel Efficiency*
Science as Inquiry							
Abilities necessary to do scientific inquiry	X	X	X	X			
Physical Science							
Properties and changes of properties in matter			X				
Motions and forces	X	X	X	X	X	X	
Transfer of energy							
Interactions of energy and matter							
Life Science							
Structure and function in living systems							
Earth and Space Science							
Earth in the solar system							
Science and Technology							
Abilities of technological design	X	X	X		X	X	X
Understanding about science and technology		X					
Science in Personal and Social Perspectives							
Populations, resources, and environments			X				
Risks and benefits							
Natural and human induced risks							

Science Process Skills

	Finding the Center of Gravity Using Rulers	*Finding the Center of Gravity Using Plumb Lines*	*Changing the Center of Gravity with Moment Arms*	*Jet Propulsion*	*Vectoring*	*Center of Gravity, Pitch, Yaw*	*Fuel Efficiency*
Observing	X	X	X	X	X		
Communication	X	X	X	X	X		
Measuring	X	X	X			X	
Collecting Data	X		X	X	X		
Inferring	X		X		X		
Predicting	X	X	X		X		
Making Models				X	X	X	
Making Graphs							X
Hypothesizing	X		X				
Interpreting Data							
Controlling Variables		X		X	X		X
Defining Operationally							
Investigating	X	X	X		X		



Grades K-4

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Lesson 1: Finding the Center of Gravity Using Rulers
Grades K–4

Objectives

- To discover the center of gravity (c.g.) by balancing a cardstock shape (two-dimensional model) of an F-15 ACTIVE on a ruler both longitudinally and laterally.
- To demonstrate balance (state of equilibrium) by suspending a cardboard shape of an F-15 ACTIVE from a string at the center of gravity (c.g.).

Science Standards

Scientific Enterprise
Science and Technology
Science as Inquiry
Physical Science
Position and Motion of Objects
Change, Constancy, and Measurement
Evidence, Models, and Explanation

Science Process Skills

Observing
Communicating
Measuring
Collecting Data
Inferring
Predicting
Hypothesizing
Investigating

Mathematical Standards

Problem Solving
Communication
Reasoning
Measuring

Management

This lesson may be a whole class lesson. For kindergarten and first grade students, the teacher may demonstrate using one cardstock model of an F-15 ACTIVE. Students in grades 2-4 may each have their own cardstock model or work in small groups of two to four sharing a cardstock model.

This lesson is divided into two parts. In part 1, students draw longitudinal and lateral axes to find the center of gravity. In part 2, students may need help to suspend models. The models are needed for lesson 3, and part 2 may be postponed until lesson 3 is scheduled. Allow approximately 30 to 45 minutes to complete.

The center of gravity is the average location of the weight of the aircraft. The mass and weight are distributed throughout the airplane.

Part 1

Materials and Tools

- Cardstock F-15 ACTIVEs (see page 21) for each student or group
- Ruler for each group
- Crayon
- Masking tape
- Scissors

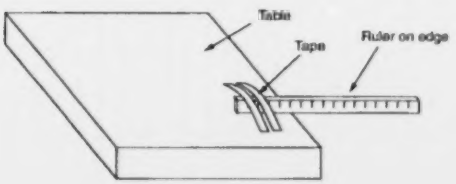
Preparation

Teacher uses the pattern to trace and cut out F-15 ACTIVE models from light cardstock (see page 21). If students are capable, they can cut out their own models.

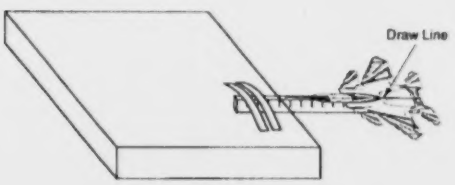
Procedure

1. Ask students what they know about the F-15. (It is a highly maneuverable fighter capable of achieving Mach 2 and high altitudes. Explain that the F-15 ACTIVE was a special one-of-a-kind airplane flown by NASA and U.S. Air Force research pilots for research purposes.)
2. Bring out a cardstock F-15 ACTIVE model. Balance it flat on your finger or fist. Ask the students if they think they could balance it too. If using one model to demonstrate, give several students a chance to balance it, or distribute the cardstock F-15 ACTIVEs. Allow time for experimentation.

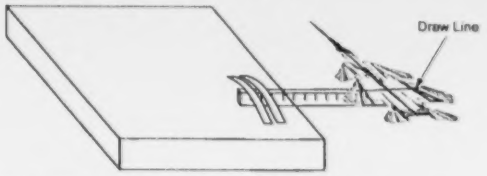
3. Tell students that NASA engineers need to know the exact place to balance the real airplane, just as they balanced their model airplanes. This place is called the center of gravity (c.g.). Balance an F-15 ACTIVE model on your finger. Tell students this is a stable position—when given a little push—it wobbles back and forth, but doesn't fall. It will come back to a stable, balanced position. Tell them NASA engineers use science and mathematics to find the center of gravity (c.g.), and they can do it too.
4. Tell students they will balance the F-15 ACTIVE models on the edge of a ruler instead of on their fingers. Demonstrate how to position the ruler on the edge of a table and tape it in place with masking tape.
5. Most of the ruler's length should extend past the edge of the table.
6. Demonstrate how to balance the cardstock F-15 ACTIVE on the ruler in a longitudinal direction. Draw a line down the middle of the F-15 ACTIVE with a crayon.



7. Demonstrate how to balance the F-15 ACTIVE on the ruler in a lateral direction. Draw a line.



8. The point of intersection of the two lines is the center of gravity (c.g.).

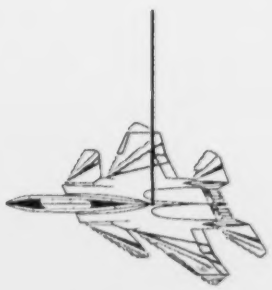


9. Distribute tape and rulers to each group. Students will tape the ruler to a desk and take turns helping each other balance and hold the F-15 ACTIVE steady so lines may be drawn. This could be a learning center with an adult helper. Save F-15 ACTIVE for part 2.

Part 2

Materials and Tools

- Cardstock F-15 ACTIVE from part 1
- Crayons
- Needle and string for teacher
- Paper clips
- Ceiling hooks
- Meter sticks or rulers



Procedures

1. Allow students to color their F-15 ACTIVEs using the colors of red, white and blue. Use the Exploring the Extreme poster as a color guide or look on-line at www.spacelink.nasa.gov. Teacher punches a small hole in each F-15 ACTIVE at the center of gravity with the needle and thread.
2. Tie a large knot on the bottom of the string. The knot must be larger than the hole.
3. Hang from ceiling using paper-clip hooks or suspend from meter stick/ruler, which will be held by the teacher or partner. Save F-15s for lesson 3.

Assessment

1. Conduct a class discussion where students demonstrate their understanding of:
   - Balance
   - Stability
   - Center of gravity

2. Ask students to predict what they think might happen if the teacher pushes the F-15 ACTIVE in:
   - A forward direction
   - A sideways direction

3. Push the F-15 ACTIVE and allow it to swing back to a resting position. Discuss the action in terms of balance and stability. Compare the push to a pilot flying (controlling) the airplane and the airplane being designed to return to a stable position. The F-15 ACTIVE uses computers to integrate the control surfaces and the vectored thrust so that the plane is stable.

Management

In part 1, students may work individually or in pairs using their F-15 ACTIVE models from lesson 1 or lesson 2. Using just one suspended cardstock F-15 ACTIVE model, the teacher may demonstrate part 1.

In part 2, students working in pairs or groups of three will be able to help each other. Allow 20–30 minutes for part 1, and 45 minutes for part 2.

Description

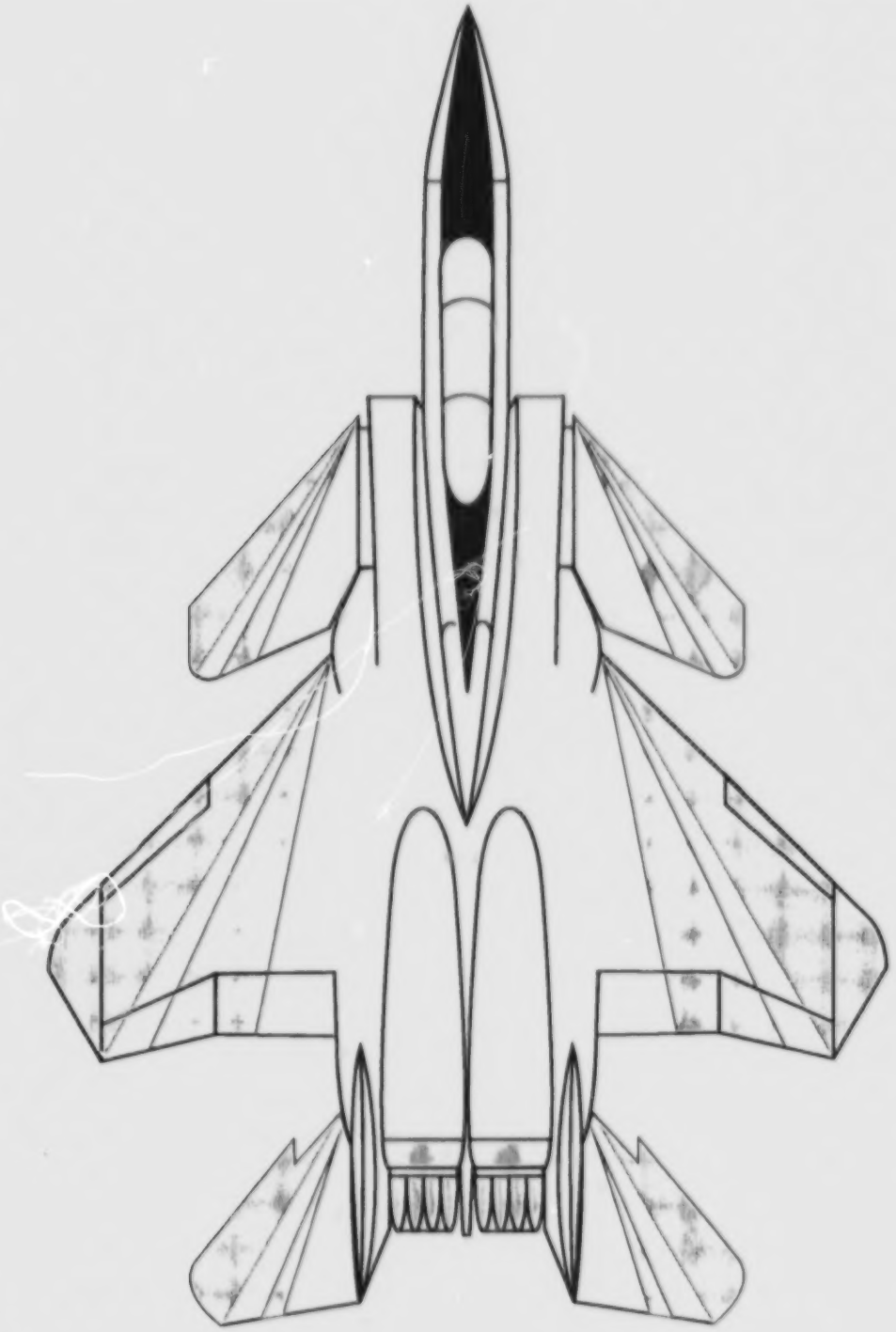
Students discover the center of gravity of a cardstock shape of an F-15 ACTIVE using plumb lines and suspend the F-15 ACTIVE from a string.

Materials and Tools

- Cardboard F-15 ACTIVEs
- String for each group, 18 inches (45.72 centimeters)
- Hole punch for each group
- 2 pushpins
- Paper clip for each group
- Ruler for each group

Drawing of F-15 ACTIVE

(Teachers, copy this page on to cardstock.)



Lesson 2: Finding the Center of Gravity Using Plumb Lines
Grades 3–4

Objectives

- To discover the center of gravity (c.g.) of a cardstock shape (two-dimensional model) of an F-15 ACTIVE using plumb line.
- To demonstrate balance (state of equilibrium) by suspending a cardstock shape of an F-15 ACTIVE from a string at the center of gravity.

Science Standards

Scientific Enterprise
Science and Technology
Science as Inquiry
Physical Science
Position and Motion of Objects
Change, Constancy, and Measurement
Evidence, Models, and Explanation

Science Process Skills

Observing
Communicating
Measuring
Investigating
Predicting
Controlling Variables

Mathematical Standards

Problem Solving
Communicating
Reasoning
Measuring
Functions and Patterns

Preparation

Use the pattern of the F-15 ACTIVE to trace and cut out cardboard shapes. Older students can do the cutting.

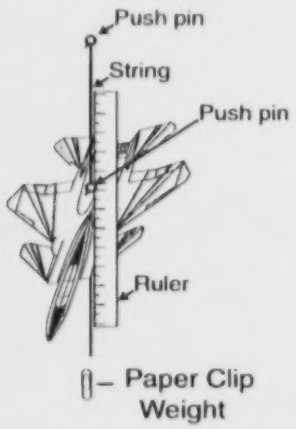
Part 1

1. Introduce the F-15 ACTIVE

- Ask students what they know about the F-15 ACTIVE. (A highly maneuverable fighter capable of achieving over Mach 2 and altitudes of 60,000 feet.) Bring out one of the cardstock F-15 ACTIVEs. Explain this as an F-15 ACTIVE, a special one-of-a-kind airplane flown by NASA test pilots for research purposes.
- Balance it flat on your finger. Ask the students if they think they could do the same if they had an F-15 ACTIVE. Challenge students.
- Distribute cardboard F-15 ACTIVEs or distribute materials so students can cut out the F-15 ACTIVEs.
- Allow time for exploration as students will want to fly their airplanes.
- Tell students that NASA engineers need to know the exact place to balance the F-15 ACTIVE just as the students did when they balanced the models on their fingers.
- Tell them NASA engineers use mathematics to find the center of gravity, and they can, too.
- Students will do each step in small groups, or teacher may demonstrate.

Procedure

1. Attach the paper clip weight to one end of a string.



2. Attach the string and paper clip weight to a wall with a pushpin. This is the plumb line.
3. Punch one hole anywhere on the F-15 ACTIVE.
4. Put the other pushpin through the hole, and let the F-15 ACTIVE dangle from the pin until it settles in a stable position.
5. Put the pushpin (and hanging F-15 ACTIVE) right on the plumb line.
6. Use a ruler to draw a line on the F-15 ACTIVE, following path of the plumb line.
7. Repeat steps 3, 4, 5, and 6 once or twice. Take turns.
8. Where the lines intersect is the center of gravity.

Part 2

Have the students color their F-15 ACTIVEs and punch a small hole in each F-15 ACTIVE at the marked center of gravity with a needle and thread. Tie a large knot at the bottom. Hang from the ceiling using paperclips or hooks. Hang the F-15 ACTIVEs low enough so that students can use them to complete lesson 3.

Assessment

1. Conduct a class discussion where students demonstrate their understanding of:
   - Balance
   - Stability
   - Center of Gravity

2. Ask students to predict what they think might happen if the teacher pushes the F-15 ACTIVE in:
   - A forward direction
   - A sideways direction

3. Push the F-15 ACTIVE and allow it to swing back to a resting position. Discuss the action in terms of balance and stability. Compare the push to a pilot flying (controlling) the airplane and the airplane being designed to return to a stable position. The F-15 ACTIVE uses computers to integrate the control surfaces and the vectored thrust so that the plane is stable.

Extensions

Use other shapes to find center of gravity. For example: initials, outlines of states, birds.

Lesson 3: Changing the Center of Gravity Using Moment Arms
Grades 3–4

Objectives

- To discover that the center of gravity (c.g.) can be changed by adding weights to the balanced F-15 ACTIVE model.
- To calculate moment arms using weights on a yardstick.

Science Standards

Unifying Concepts and Processes in Science
Science as Inquiry
Physical Science
Positions and Motion of Objects
Science and Technology
Science in Personal and Social Perspectives
History and Nature of Science

Science Process Skills

Observing
Communicating
Measuring
Investigating
Predicting
Collecting Data
Inferring
Hypothesizing

Mathematical Standards

Problem Solving
Communicating
Reasoning
Computing and Estimating
Measuring
Functions

Management

In part 1, students may work individually or in pairs. In part 2, students working in pairs or groups of three will be able to help each other. Allow 20-30 minutes for part 1 and 45 minutes for part 2.

Description

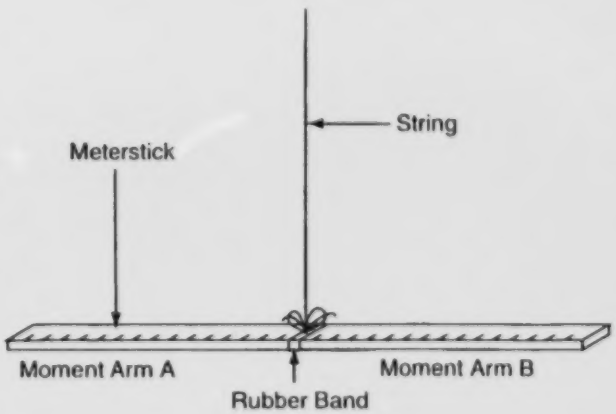
Students discover the center of gravity can be changed by adding paper clips to the balanced F-15 ACTIVE cardboard model.

Students calculate the moment arm using a balanced yardstick, adding weights at measured differences.

Materials and Tools

For each group:

- Yardstick
- Rubber band
- String
- Cellophane tape or masking tape
- Ruler
- Weights:
  - -Government Standard weight set (1, 2, 3 grams) or
  - -Fishing sinkers of known weigh (1, 2, 3 ounces) or
  - -Fishing sinkers all one size per group
- Copy of chart for each student



Preparation

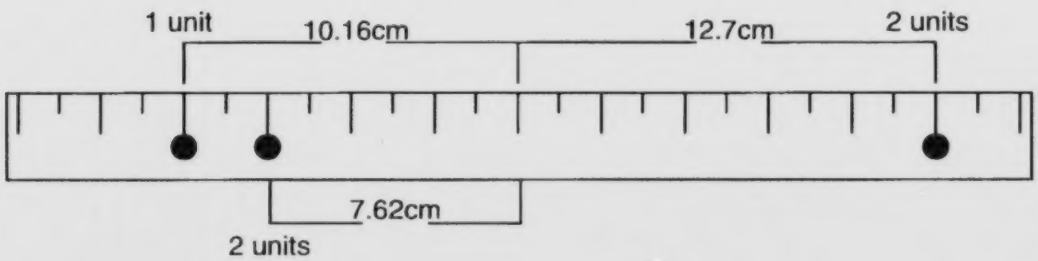
The teacher may want to arrange the hanging yardsticks before class time. Each group will use a suspended yardstick. Wrap a rubber band around each yardstick. Tie a string to the rubber band to suspend the yardstick. Move the rubber band until the yardstick is balanced. Rubber band is at the 0 point and measurements will be made in both directions, called arms, starting at this point. Explain that moment is equal to weight x moment arm (distance). Calculate moments for tests 1-4.

1. Tell students to place a 1-unit weight 2 inches (5.08 cm) from the 0 point. They should tape it to the yardstick. Suspend the yardstick. It will be unbalanced. Tell students to find out how much weight needs to be placed at 1 inch (2.54 cm) from the 0 point on the other side to make the yardstick balance. Record the answer on chart. *(2 units weight)*
   Discussion: Ask if the larger weight is closer or farther away from 0 point. Will this always be true? *(Yes, the larger weight is always closer to the 0 point.)*
2. Tell students to put 2 units of weight at 6 inches (15.24 cm) from the 0 point. Ask them to find what weight needs to be added at 4 inches (10.16 cm) from the 0 point on the other side. Record the answer. *(3 units weight)*
   Discussion: The distance the weight is from the 0 point is called the moment arm. One side is called weight A on moment arm A and the other side is weight B on moment arm B. Look at chart.
3. Tell the students to put 3 units of weight 4 inches (10.16 cm) from 0 point. (3 units weight at 4 inches or 10.16cm moment arm.) Ask where they could put a 1-unit weight to make the yardstick balance. Record the answer. (*12 units*)
4. Put 2 units of weight on one side to make the yardstick balance. It will be easier if students use even measurements. Record the answer.
   Discussion: Ask if students notice a connection between moments A and B.
   - How do you find moment?
   - What is the difference between moment and moment arm?
5. Let students experiment with weights to get other moments.
   Enrichment: Challenge students to add weights to two different spots on the same side.
   Weight A_1 x Moment arm_1 + Weight A_2 x Moment arm_2 =
   Weight B x Moment arm B
   $1 \times 4 + 2 \times 3 = 2 \times 5$

Assessment

Discussion and Student Sheet

A	B
1. 1 x 2 = 2	1. 2 x 1 = 2
2. 2 x 6 = 12	2. 3 x 4 = 12
3. 3 x 4 = 12	3. 1 x 12 = 12
4. 2 x 3 = 6	4. 3 x 2 = 6 (possible answer)
5. 2 x 6 = 12	5. 3 x 4 = 12 (possible answer)
6. 2 x 9 = 18	6. 3 x 6 = 18 (possible answer)



Name: _____

Date: _____

Moment Student Work Sheet

Test #	Weight A (Grams)	Distance A (Moment Arm A, Centimeter)	Moment A (Grams centimeter)	Weight B (Grams)	Distance B (Moment Arm B, centimeter)	Moment B (Grams centimeter)
#1	28.35g	5.08cm		56.7g	2.54cm	
#2	56.7g	15.24cm		85.05g	5.08cm	
#3	85.05g	10.16cm		28.35g	30.48cm	
#4	56.7g	7.62cm				
#5						
#6						
#7						

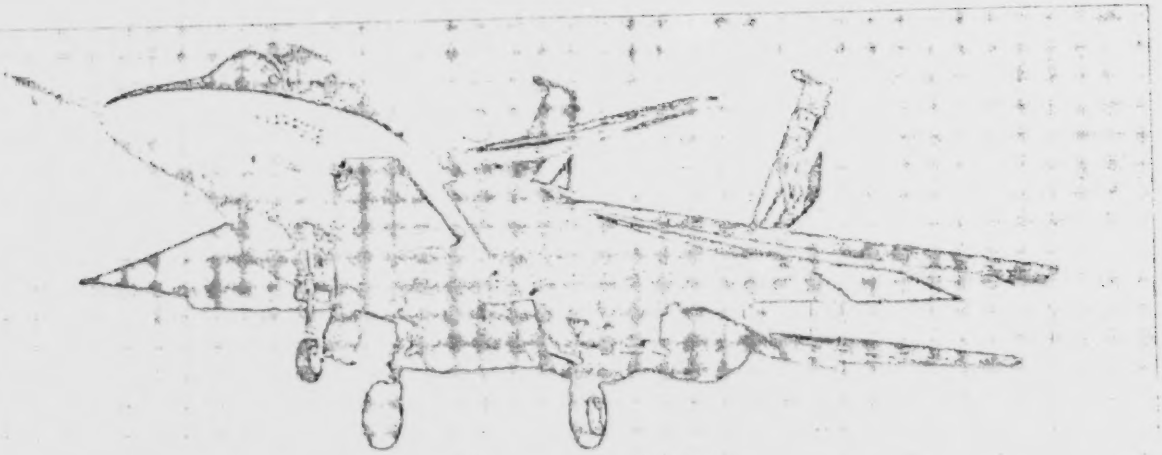
Name: _____

Date: _____

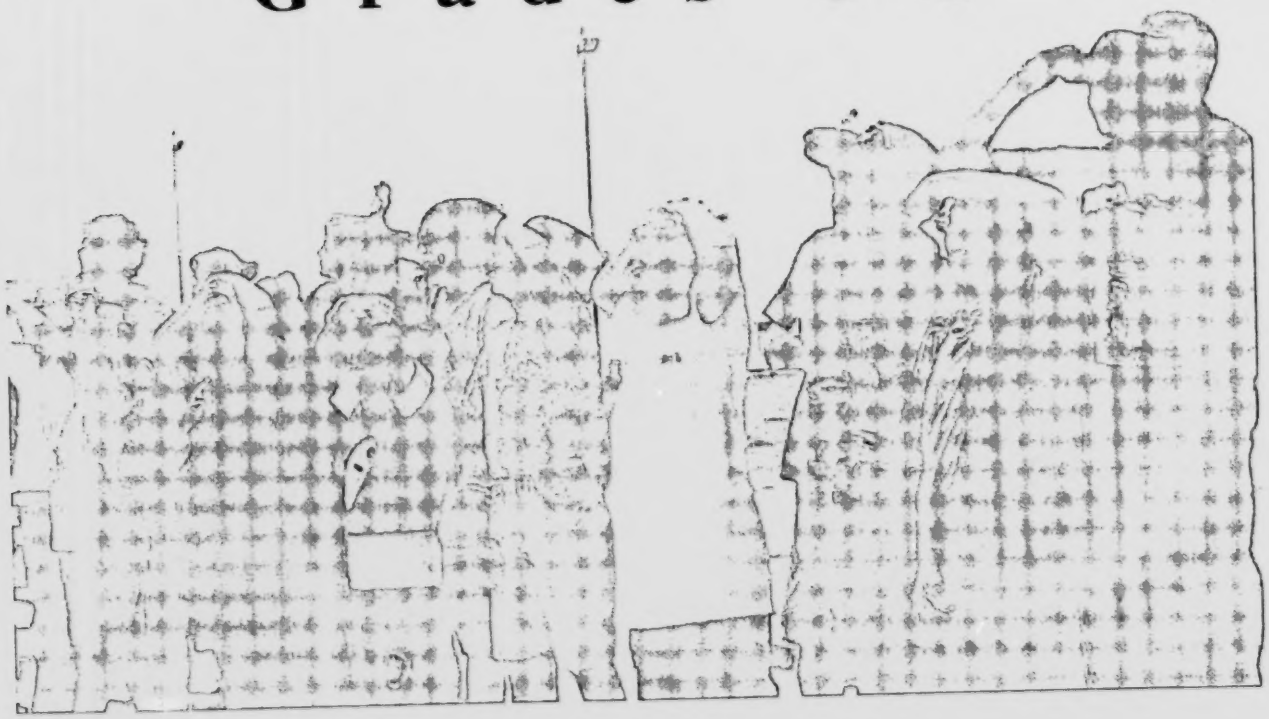
Enrichment

Calculate these moments. Use calculators if appropriate.

Item	Weight (Kilograms)	Moment Arm (Meters)	Moment Kilograms
Fuel in tank 1	4409.2 (9720 lbs.)	32.808 (1291 in.)	
Fuel in tank 2	2204.6 (4860 lbs.)	16.404 (645 in.)	
Fuel in tank 3	3306.9 (7290 lbs.)	13.1232 (516 in.)	
Fuel in tank 4	2204.6 (4860 lbs.)	26.2464 (1033 in.)	
Instruments	209.437 (461 lbs.)	9.8424 (387 in.)	
Pilot (Student Weight)		16.404 (645 in.)	



Grades 5-8



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Lesson 1: Jet Propulsion
Grades 5 - 8

Objective
- To build a model to demonstrate how thrust is created in a jet engine.

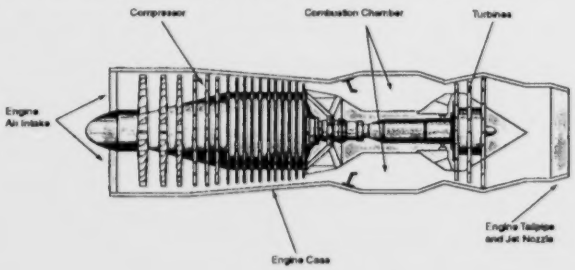
Science Standards
Science as Inquiry
Physical Science
Position and Motion of Objects
Unifying Concepts and Processes
Evidence, Models, and Explanation

Science Process Skills
Observing
Communicating
Collecting Data
Making Models
Controlling Variables

Mathematics Standards
Communicating
Reasoning
Connections

Management
This activity works best if the students work in pairs. Allow approximately 40-45 minutes to complete. This is activity is divided into two parts. In part 1 the students move through the three stations discovering what happens as different forces act on air. Then students process what they observed and compile it into the correct arrangement to describe how a turbojet engine produces thrust. This experiment stresses prediction, observation, data collection, and analysis of results. In part 2 the students construct a model of a jet engine, label each part, and describe what each part does. An optional teacher demonstration may be used to bring the three stages together into a single event.

Background Information
A turbine engine works in four basic stages. Outside, or ambient, air enters the engine through the air inlet. The air then moves into the compression section of the engine. In this section the compressor increases the air pressure, which also increases its temperature. From there the air is forced into the burner section, where the temperature is further increased by fuel combustion. The hot, expanding air then moves into the turbine, which drives the compressor. The air expands through a tailpipe designed to discharge the exhaust gas at high velocity, producing thrust.



Description
Using a series of stations, students discover how an engine takes in air, compresses it, burns fuel to make air expand, and how the air is then forced out the tailpipe, creating thrust. There is also an optional teacher demonstration combining all these components into a single tennis ball–container engine.

Part 2 involves building a static, or non-moving, model of a jet engine. At the end of the lesson, students will use technical writing skills to explain how a jet engine works.

Part 1
Materials and Tools

- **Intake Station**
  - Small desk fan
  - One sheet of paper
  - Intake Station Directions
- **Compression Station**
  - Butcher paper
  - Two desk fans that are the same size
  - Twenty 6-inch lengths of string
  - Twenty 5-by-7-inch index cards
  - Tape
  - Two markers
  - Compression Station Directions
- **Combustion Station**
  - Flask, medium size
  - Balloon
  - Can of Sterno
  - Matches or lighter
  - Tongs
  - Combustion Station Directions

Procedures

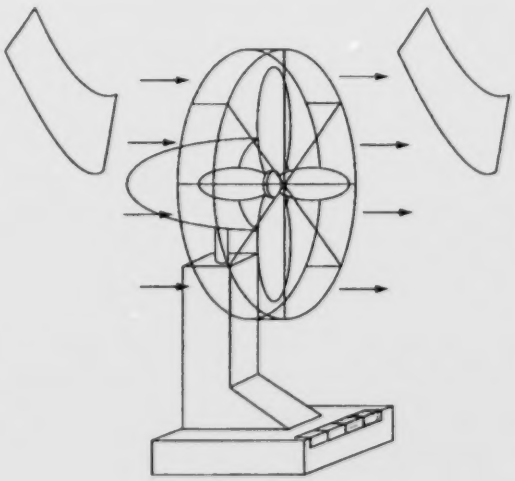
1. Prior to the start of school, set up the equipment at the three stations. If there is room you may want to set up several stations to improve classroom management and increase student participation. Make sure the fans are in good working order.

   Intake Station: Plug in the electric fan. Lay a few pieces of paper near the fan. Post the direction sheet on page 39 where it can be seen easily.

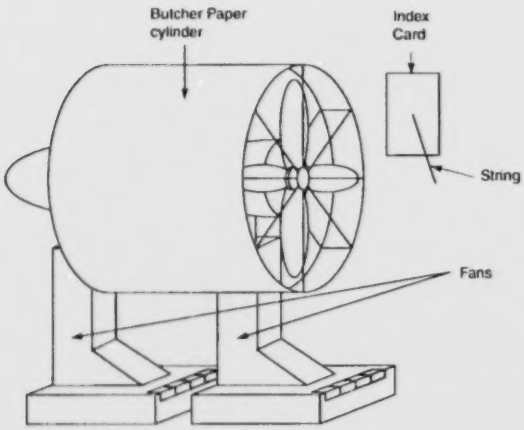
   Compression Station: Line up two fans, one in front of the other, pointing the same direction. Using butcher paper make a cylinder that will fit precisely around the frames of the fans. Tape the ends of the cylinder to the fans. Set out index cards, markers, string, and tape. Post the direction sheet on page 40 where it can be seen easily.

   Combustion Station: Stretch the balloon over the neck of the flask. Set out the Sterno can, matches, and tongs. You will want to monitor this station closely because of the use of heat and matches. Post the direction sheet on page 41 where it can be seen easily.
2. Distribute Student Work Sheet. Tell the students they will be conducting various experiments at the stations situated around the room.
3. Move around the room and read the directions for each station and demonstrate them with the fans turned off and the Sterno can unlit.

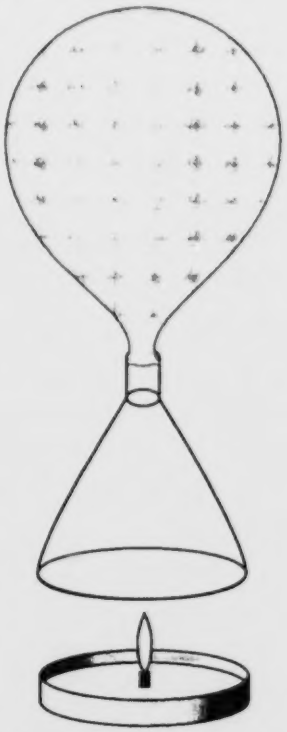
   Intake Station: Tell students to turn on the fan when they get to the station. Hold the piece of paper in front of the fan. Record what you observe. Next hold the paper behind the fan. Record what you observe.



Compression Station: Show the students how to poke a hole in the middle of the index card. Then put one end of the string through the hole and tape it to the index card. About 5 inches of the string should be hanging free. Tell them to turn on the fan. Then they will hold the index card 2 to 3 inches away from the front of the fan. The string should hang free. Using the marker, the students will mark how high the string is blown. Then the back fan will be turned on. With both fans blowing, the students will again hold the index card and string in front of the air stream and mark the height of the string. Record what you observe.



Combustion Station: Carefully light the Sterno can. Using the tongs hold the flask over the Sterno can for a few minutes. Observe what happens to the balloon. Record what you observe. Answer the questions on the student record sheet on page 42.



4. Prior to allowing the students to conduct each experiment, have them write their predictions for each activity. Set a time limit of approximately 15 minutes and allow the students to move around the room and conduct each experiment and answer the questions.

Discussion Questions

1. What did you observe at station 1 with the paper and the fan? Did this match your prediction? *The paper that is held in front is blown away from the fan. The paper held in the back is sucked in towards the fan.*
2. What was your prediction for what would happen if the air had been moving into the front fan instead of being still? What actually happened? *The air speed increases when the air behind the fan is blown into the fan rather than being still.*
3. What happened to the balloon at station 3? Why do you think this happened? What would happen if the air was enclosed in a tube that didn't expand instead of inside a balloon? *The balloon inflated because the air inside was heated. Heated air expands. If this had taken place in a tube, the air would have been forced out the end of the tube.*
4. All these stations demonstrate the processes that take place inside the various parts of a jet engine. In what order do you think they take place? Why? *The proper order of the stations is intake, compression, and combustion. There is an additional step of using a turbine to move the air out of the engine. This was not demonstrated. According to one NASA engineer, a shorthand way to remember the steps is "suck, squeeze, burn, and blow."*
5. Describe to the class the process an engine uses to produce thrust. A jet engine's compressor turns like the blades of a fan. This causes air to be drawn in from the outside. When the air moves through the compressor, which is a series of fans, it is compressed or squeezed. After moving through the compressor, the air enters the combustion chamber. In the combustion chamber jet fuel is ignited by the igniters, which are similar to spark plugs, which heats the compressed air, forcing it to expand. The rapidly expanding air is forced through a turbine, which causes it to turn and drive the compressor. The turbine is connected to the compressor by a shaft. The air then flows out the tailpipe.

Part 2

Materials and Tools

- One cardboard paper towel core per student
- One flexible straw per student
- One 12-by-12-inch sheet of aluminum foil per student
- Four paper circles 1-1/2 inches in diameter per student
- One small (1-inch) paper clip per student
- One 3-oz. paper cup per student
- One pair of scissors per student
- Tape
- Glue (not glue sticks)
- One copy of the Student Work Sheet Part 2 for each student (see page 44).

Procedures

1. Cut the paper towel core in half lengthwise (figure 1).

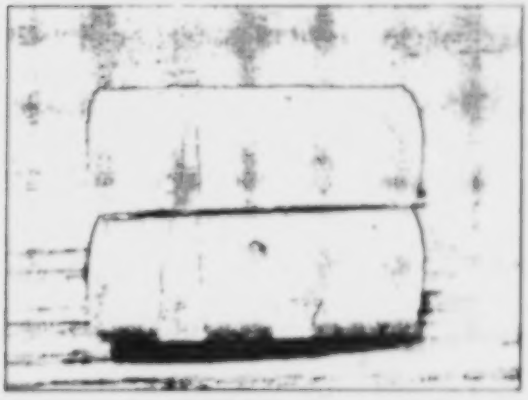


Figure 1

2. Tape the halves together on one side to create a hinge effect. This will make it easier for the students to put the pieces together.
3. Cover the halves with foil. This is strictly for appearance.
4. Using the pencil, poke a hole in one side of the toilet-paper core halfway down the core. Make the hole large enough for the straw to fit into it.

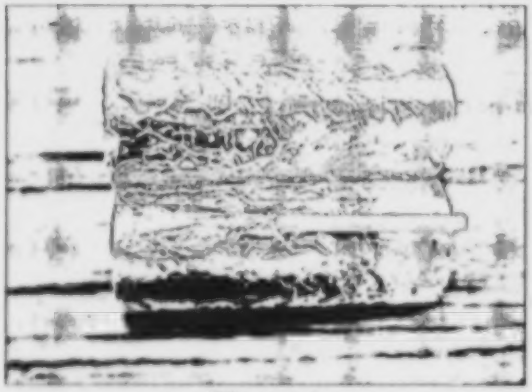


Figure 2

5. Cut the straw down so it is 1/4 inch long on one side of the flexible section and about 1 inch long on the other side.
6. Put the short end of the straw into the hole, bend the straw so the longer end lays flat against the paper towel core. Tape into place. This represents the fuel line (figure 2).
7. Fold the paper circles in half then into quarters. Open the circles.
8. Cut along the folds close to the center but do not cut through the center. Do this on the remaining circles too.

Figure 3

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9. Bend one corner from each section so the circles resembles a fan. Do this for two more circles also (figure 3).
10. Straighten the paper clip. Then bend approximately 1/2 inch of the paper clip down on one end. This will keep the paper fans from sliding off the paper clip.
11. Push the end of the paper clip into the center of one fan. Slide the fan back so it is resting against the bent end of the paper clip. Wrap a narrow piece of tape around the paper clip to act as a spacer and to provide stability. Repeat this step with two of the three remaining fans.
12. Wrap a narrow piece of tape 1 inch from the straight end of the paper clip. Place the remaining fan onto the paper clip to serve as the turbine, wrap a final piece of tape around the paper clip to keep the fan in place (figure 4).

Figure 4

13. Install the compressor and turbine unit into the engine by placing glue inside the tube where the edge of the fans will touch the sides of the tube on the same side as where the hole was made for the fuel line. Hold the fans in until glue is partially dry (figure 5).

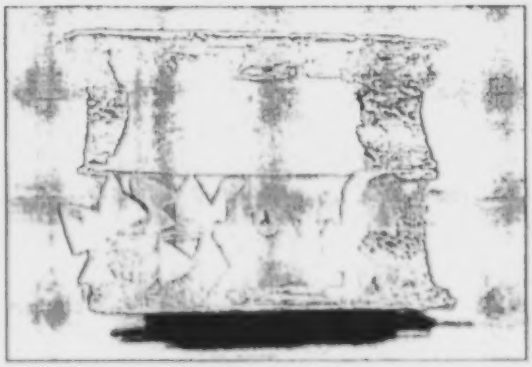

Figure 5

14. Tape the paper towel core shut.
15. Cut down the length of the paper cup and cut the bottom out of it.
16. Put the cup back together overlapping the edges.
17. Insert it into the paper towel roll, large end first. Ease the paper cup open until it snugly fits inside the toilet paper roll. Tape the edge of the cup on the inside to hold its shape. The cup will move easily but should not fall out. This represents the tailpipe and the movement of the tailpipe with thrust vectoring (figure 6).

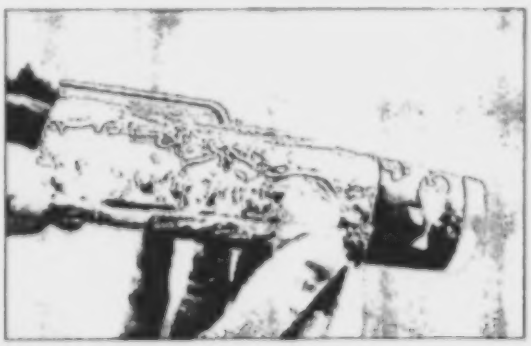

Figure 6

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Discussion

1. Based on the experiments and the follow-up discussion, what is the purpose of each part of the engine? *The air intake brings ambient, or outside,air into the engine. The compression section moves the air through a series of fans that compress, or squeeze, the air causing it to increase in speed. The combustion section heats the air by burning fuel. This causes the air to expand very rapidly and significantly increases its speed again. Finally, the turbine forces the heated, expanding air out the back of the engine, creating thrust.*

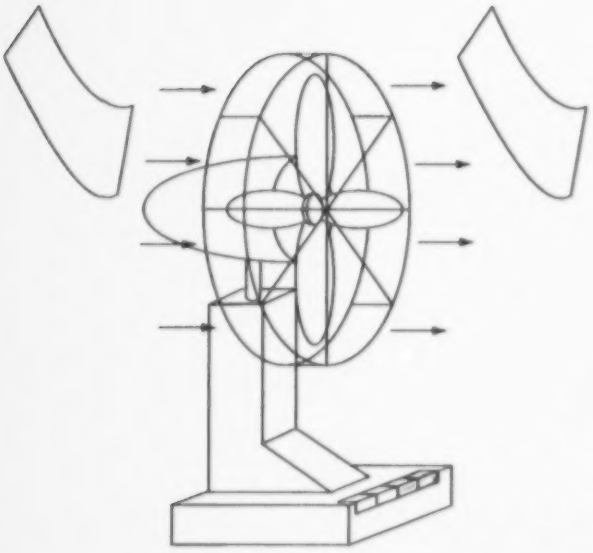
Assessment

Conduct a class discussion where students share their findings about how a jet engine works. Have them complete the jet engine work sheet by describing the function of each part of the jet engine. As an optional activity, instead of the Student Work Sheet, the students could be given a blank sheet of paper and instructed to draw a jet engine cross section using their model and then describe the function of each part. Collect and review completed student worksheets.

Intake Station Directions

Make sure to fill in the description and prediction sections on your Jet Propulsion Work Sheet *before* doing the experiment.

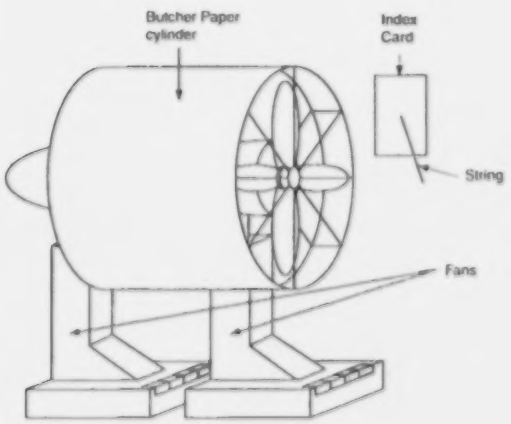
1. Turn on the fan.
2. Hold a piece of paper in front of the fan. Observe what happens.
3. Next, hold the paper behind the fan. Observe what happens.
4. Record your observations on your Student Work Sheet. Make sure to explain not only what happened but also why you think it happened.



Compression Station Directions

Make sure to fill in the description and prediction sections on your Jet Propulsion Work Sheet *before* doing the experiment.

1. Take one of the index cards and poke a hole in the center of it using your pencil.
2. Thread about an inch of the string through the hole. Tape the inch of string to the index card. The free end of the string will move in the air current to help determine the relative speed of the air coming out of the fan.
3. Turn on only the front fan.
4. Hold the card in front of the fan so the long edge of the index card is about three inches from the front of the fan. Angle the card so that the string is blown by the air current coming from the fan.
5. Use a marker to mark how high on the card the string moved.
6. Leave the front fan on and turn on the rear fan.
7. Hold the card in front of the fan again.
8. Again, mark how high on the card the string moved.
9. Record your observations on your Student Work Sheet. Make sure to explain not only what happened but also why you think it happened.



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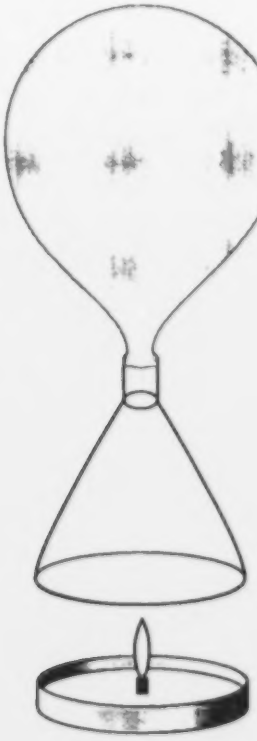
Combustion Station Directions

Make sure to fill in the description and prediction sections on your Jet Propulsion Work Sheet *before* doing the experiment.

1. Pick up the flask using the tongs.
2. Hold the flask one to two inches above the flame from the Sterno can.
3. Wait and watch the balloon.
4. Record your observations on your Student Work Sheet. Make sure to explain not only what happened but also why you think it happened.



Student Work Sheet Part 1

Name:_____

Date:_____

Jet Propulsion

You may do the experiments in any order you choose. Complete these steps at each station:

1. Describe the experiment in your own words.
2. Predict what will happen during the experiment. Do this BEFORE conducting the experiment.
3. Conduct the experiment.
4. Record your observations and give your opinion as to why the experiment worked as it did.

_____

Intake Station

Describe the experiment: _____

_____

_____

Make your prediction: _____

_____

_____

Record your observations: _____

_____

_____

Compression Station

Describe the experiment: _____

_____

_____

Make your prediction: _____

_____

_____

Record your observations: _____

_____

Combustion Station

Describe the experiment: _____

_____

_____

Make your prediction: _____

_____

_____

Record your observations: _____

_____

_____

These three stations demonstrate different parts of a jet engine and how it works. Based on your observations, describe how you think a jet engine works.
NOTE: One of the stations has to be used twice.

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

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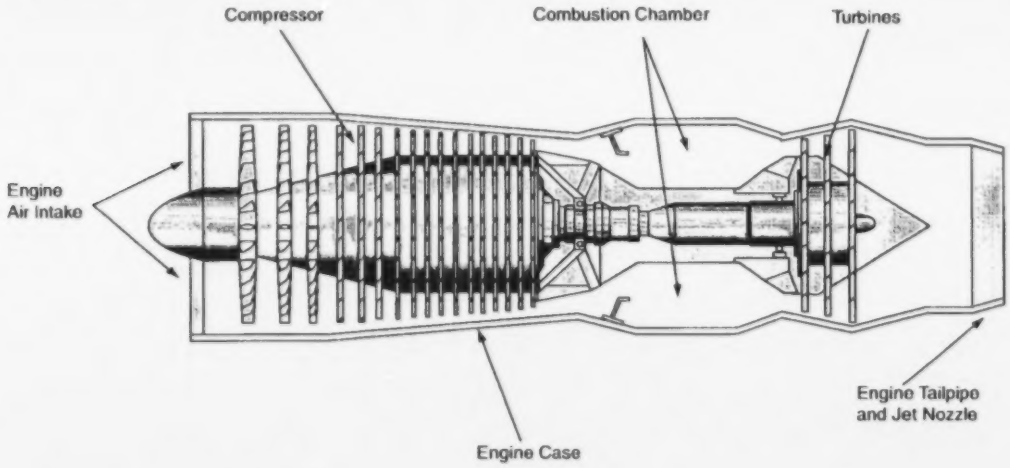
Student Work Sheet Part 2

Name:_____
Date:_____

Jet Propulsion Work Sheet

Describe the function of each part of the jet engine pictured below and state the scientific concepts that occur.



Air inlet (also intake)

_____

_____

Compressor

_____

_____

Fuel line

_____

_____

Turbine

_____

_____

Jet nozzle

_____

_____

Lesson 2: Vectoring
Grades 5 - 8

Objective
- Discover how vectoring the thrust from a jet engine affects movement of an airplane.

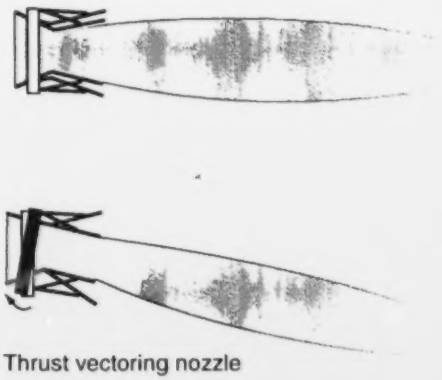
Science Standards
Physical Science
Position and Motion of Objects
Unifying Concepts and Processes
Evidence, Models, and Explanation
Science and Technology
Technical Design Abilities

Science Process Skills
Observing
Communicating
Collecting Data
Predicting
Inferring
Making Models
Controlling Variables
Investigating

Mathematical Standards
Communicating
Reasoning
Geometry

Management
This lesson can be done with the students working in pairs or individually. Allow approximately 40-45 minutes to complete. The activity in divided into two parts. In part 1 the students will cut out the picture of the F-15 ACTIVE template on page 56, put together the balloon engine, and attach it to the template. In part 2 students will control the direction of the thrust from the balloon by bending the flexible straw in different directions. This experiment stresses prediction, data collection, and analysis of results.

Background Information
Controlling and directing the angle of the thrust that comes out of an engine is called thrust vectoring. This is the purpose of the F-15 ACTIVE research project. Thrust vectoring will make future aircraft more maneuverable and more fuel efficient. Currently thrust can be vectored at a 20° angle in any direction. Also, the two engines can work independently of each other, meaning the nozzle thrust can be angled different directions at the same time. Thus the airplane's roll, yaw, and pitch can be controlled in this way. This is an application of Newton's Third Law of Motion: for every action there is an equal but opposite reaction.



Thrust vectoring nozzle

Description
Students cut out a copy of a picture of the F-15 ACTIVE, tape a balloon and flexible straw "engine" to the plane, and conduct a series of experiments by changing the angle of the straw. This is a simulation of thrust vectoring.

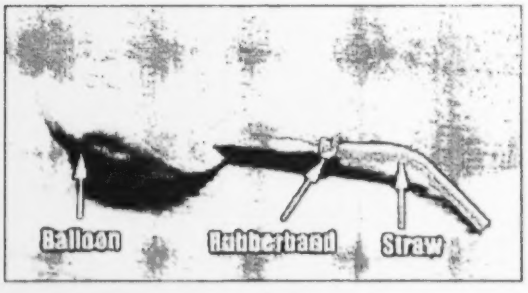
Part 1

Materials and Tools

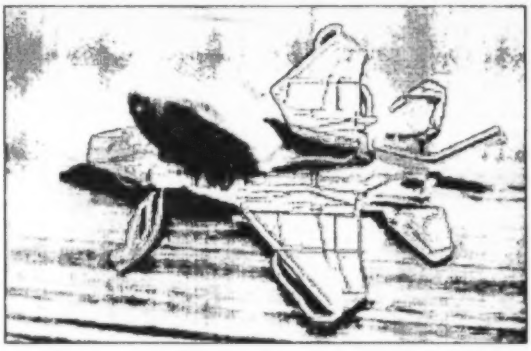
- One 8-by-10-inch F-15 ACTIVE template on page 56, photocopied on cardstock, per student
- One balloon per student
- One 1-inch section of 1/4-inch rubber tubing per student (example: fish tank tube).
- One small rubber band per student
- One pair of scissors per student
- Tape
- Three 8-inch pieces of string per student
- One copy of the Student Work Sheet per student

Procedures

1. Cut out the picture of the F-15 ACTIVE on page 56. Set aside.
2. Cut the straw so there is about 1 inch between the flexible section and each end of the straw.
3. Cut a 1/2-inch slit in one end of the straw. Gently push one end of the rubber tubing into the end of the straw with the slit. This will keep the straw from collapsing when the rubber band is wrapped around it.
4. Slide the neck of the balloon over the end of the straw with the rubber tubing in it.
5. Wrap the rubber band around the balloon, the straw, and the rubber tubing. This will create an airtight seal and allow the balloon to be inflated.

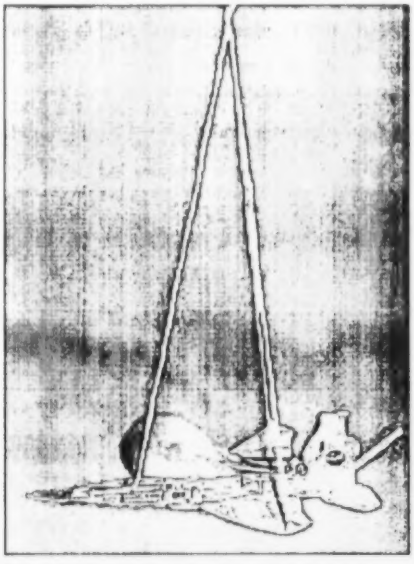


6. Position the balloon engine on the plane so that the flexible section of the straw extends beyond the edge of the plane. The balloon should rest on the plane. Tape the engine to the plane across the rubber-banded section.
7. Using the scissors, carefully poke a hole in the plane approximately where the cockpit is and one near the tip of each wing. See



hole locations marked on the template on page 56.

8. Thread one end of each piece of string through the holes. Tie a knot in each string underneath the plane to keep it from slipping off.



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9. Gather the free ends of the string together, adjust them so the plane hangs level, and tie or tape the ends together.

Part 2

Materials and Tools

- Completed F-15 ACTIVE model from part 1
- Student Work Sheet on pages 48 and 49

Procedures

1. Tell the students they are going to do an experiment to find out how the plane will react when the direction of the thrust from the balloon is changed.
2. Provide each student with a copy of the Student Work Sheet on pages 48 and 49. Instruct them to record their predictions, giving as much detail as possible, prior to conducting the experiments.
3. Ask the students to predict what they think might happen when the balloon is inflated and pinched shut, the straw is pointed at a 20° angle left, and then the straw is released so the air is forced out of the balloon through the straw. Give them time to record their predictions.
4. Have the students conduct the experiment and record their observations on the Student Work Sheet.
5. Repeat the experiment with the straw bent 20° to the right. Make sure they record their predictions first.
6. Next, have them conduct the experiment with the straw pointed 20° up, then again with the straw bent down. When they point the straw up or down, the students will need to hold the plane with their thumb and finger near the cockpit and not use the strings at all. Tell the students to pay attention to how the paper plane bends before inflating the balloon and while the balloon is deflating. The movement for these two experiments is very small, but can be detected, if they watch closely.
7. Discuss the results of each group's experiments. Did the predictions match the results? Why or why not?

Assessment

Collect and review student worksheets.

Extension

Construct two balloon engines and attach to the model to simulate the directional independence of the two F-15 ACTIVE engines.

Student Work Sheet (Part 2)

Name: _____

Date: _____

Experimenting with Thrust Vectoring

Complete these steps prior to conducting each experiment:

1. Describe the experiment in your own words.
2. Predict what will happen during the experiment. Do this *before* conducting the experiment.
3. Conduct the experiment.
4. Record your observations and give your opinion as to why the experiment worked as it did.

Thrust vectored 20° left

Describe the experiment:

_____

_____

Make your prediction:

_____

_____

Record your observations:

_____

_____

Thrust vectored 20° right

Describe the experiment:

_____

_____

Make your prediction:

_____

_____

Record your observations:

_____

_____

Thrust vectored 20° up

Describe the experiment:

Make your prediction:

Record your observations:

Thrust vectored 20° down

Describe the experiment:

Make your prediction:

Record your observations:

Lesson 3: Center of Gravity, Pitch, Yaw
Grades 5 - 8

Objective
- Find the center of gravity and discover its relationship to thrust vectoring, pitch, and yaw.

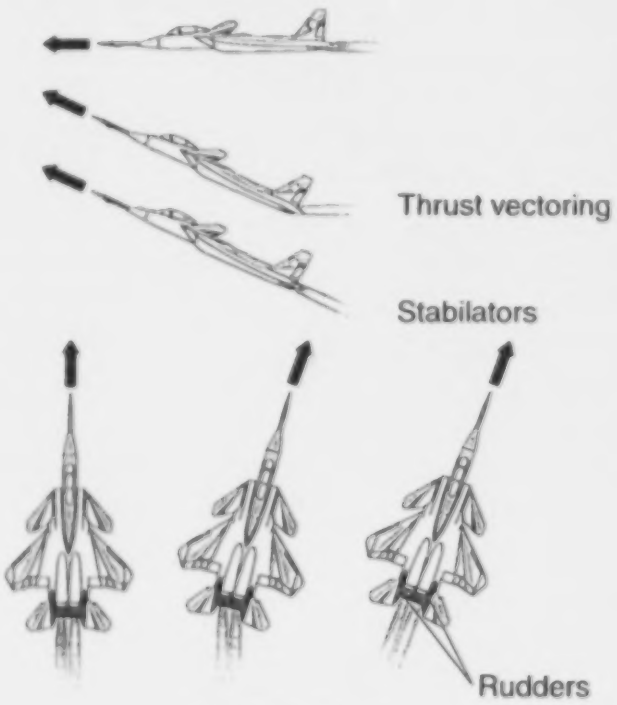
Science Standards
Physical Science
Position and Motion of Objects
Unifying Concepts and Processes
Evidence, Models, and Explanation
Science and Technology
Technological Design Abilities

Science Process Skills
Measuring
Making Models

Mathematical Standards
Connections
Computing and Estimating
Measuring

Management
This lesson works well with students working individually but helping each other through the construction section. Allow approximately two 40- to 45-minute class periods to complete. This lesson is divided into two parts. In part 1, students will calculate the location of the center of gravity using the average wing chord formula. Once this has been calculated, the students will mark the center of gravity's location on the picture of the plane from lesson 2. The students may need to use a paper clip to make sure the plane balances at the 25% chord point. In part 2 the students construct a model of the F-15 ACTIVE by marking the center of gravity on the smaller pictures, cutting out the two views of the planes and the engines, and attaching them to the student worksheet. Following a discussion of center of gravity, pitch, and yaw, the students will label the two pictures to show their understanding of pitch and yaw and correctly label the position of the center of gravity.

Background Information
To find the center of gravity, engineers weigh the aircraft, usually at the wheel points, then calculate the balance point of the airplane. For conventional airplanes, this is usually approximately 25 percent of the average wing chord and along the center line of the fuselage. When the plane moves in the pitch axis, the plane moves around the center of gravity, with



Thrust vectoring

Use of propulsion controls in place of aerodynamic controls

the nose going up or down. In current aircraft designs this is accomplished with the use of the elevators. Elevators can be part of the horizontal tail or, as on the F-15 ACTIVE, the entire horizontal tail can move to serve as elevators. Similarly, when the plane moves in the yaw axis, it rotates around the center of gravity, with the nose moving left or right. Research was conducted on how thrust vectoring affects pitch and yaw control on the F-15 ACTIVE. Like the elevators and rudder, pitch and yaw are changed by altering the angle of thrust. In addition to thrust vectoring, the F-15 ACTIVE has canards forward of the wings, which are also used to change pitch.

Description

Students will measure and calculate 25 percent of the average wing chord using the drawing of the F-15 ACTIVE from lesson 2. Using this calculation they will find the center of gravity. Students will then put together a model of the F-15 ACTIVE and label the diagram based on two views, one showing pitch, the other showing yaw.

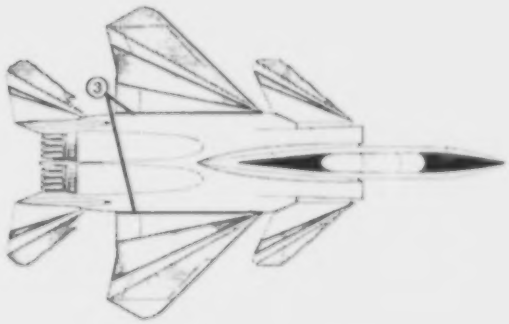
Part 1

Materials and Tools

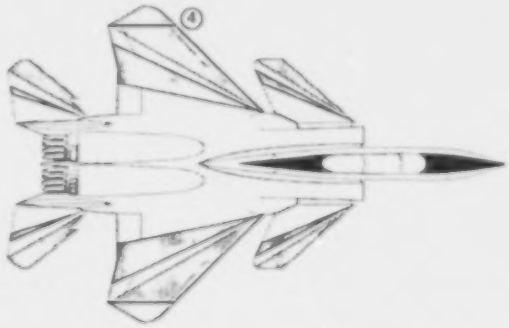
- Paper model of F-15 ACTIVE from lesson 2 on page 21.
- One metric ruler per student
- Calculators
- One copy of the Student Work Sheet Part 1 for each student (see page 54).
- Optional: an overhead copy of the F-15 ACTIVE pattern from lesson 1, page 21, for teacher use

Procedures

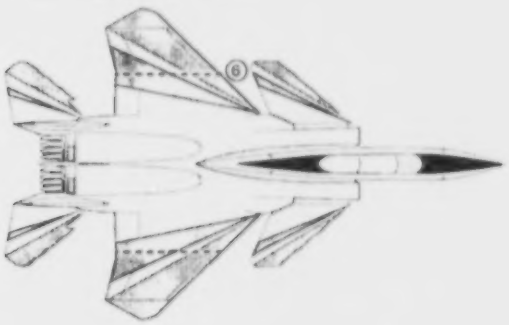
1. Have the students balance their ruler on one finger, moving the ruler back and forth until it is level. Explain that this is one way to find the center of gravity of an object.
2. Ask the class if they have any idea how engineers find the center of gravity of an airplane. Lead them to the use of a formula to calculate the center of gravity.
3. The students will do this using their pattern from lesson 1 (page 21). To find the center of gravity, first they need to measure the width of the wing next to the fuselage to the nearest millimeter. Record this number on the Student Work Sheet on page 54.



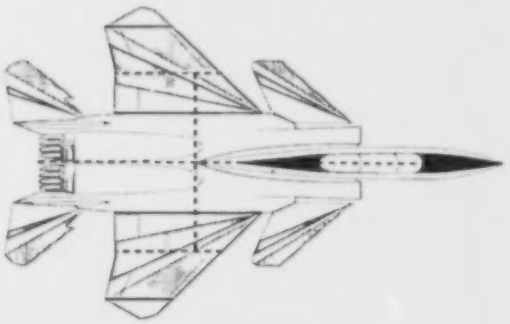
4. Next, measure the width of the wing at the wing tip and record this measurement.

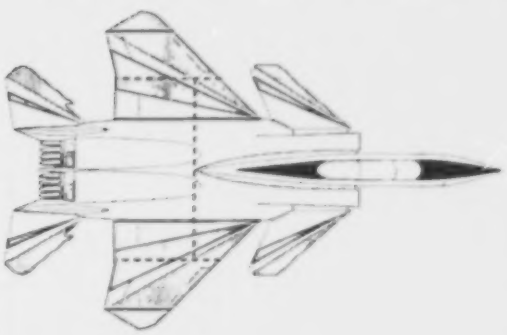


5. Have the students calculate the average wing chord by adding the two measurements, then dividing the answer by two. Record the answer on the student worksheet.
6. Using the ruler, making sure it is placed parallel to the fuselage, locate the section of the wing that matches the width of the average wing chord.



7. Students should draw a line across the wing at this point.
8. Next the students will calculate 25 percent of the length of the wing chord.
9. Mark the 25 percent wing chord distance on the line they drew for the average wing chord. This distance should be measured from the front, or leading, edge of the wing. Do this on both wings.
10. Use a straight edge to draw a line connecting the two dots.
11. To find the center of the plane lengthwise the students can simply fold the plane in half, making sure to match the edges.
12. Mark a large dot on the plane where the center lengthwise fold and the line connecting the wing chords intersect. This is the center of gravity.





Part 2

Materials and Tools

- F-15 ACTIVE model from lesson 1 (page 21).
- One cardstock copy of top and side view of F-15 ACTIVE and engines per student (see page 56).
- 4 small brads or paper fasteners per student
- Scissors
- One copy of the center of gravity, pitch, and yaw worksheet per student (see page 55).

Procedures

1. Discuss the direction the tail and nose moved when the thrust was directed left or right in lesson 2. This is yaw.
2. Check for understanding by having the students hold up their planes and demonstrate the motion when changing yaw.
3. Explain that pilots change the yaw during crosswind landings. If a wind is blowing across the runway the pilot will need to change the yaw to compensate for the push of the wind across the plane. This will allow the pilot to land safely.
4. Discuss the direction the tail moved when the thrust was directed up or down in lesson 2. This is pitch. Pitch also controls the movement of the nose of the plane. When the tail moves up the nose points down. When the tail is down the nose points up. Because of the necessity of holding the plane by the nose, the students could not see the movement of the nose during this portion of lesson 2.
5. Check for understanding by having the students hold up their planes and demonstrate the motion when changing pitch.
6. Explain that pilots change the pitch in order to change the angle of attack of the plane, which affects the amount of lift generated by the wings.
7. Construct the model of the F-15 ACTIVE following the directions below and on the Student Work Sheet.
8. Mark the center of gravity on the top and side views of the F-15 ACTIVE.
9. Cut out the F-15 ACTIVE views and engines.
10. Attach the engines to the plane using one brad for each view. Put the brads through the dots on the engine pieces and the engine area on the plane. This will simulate the thrust vectoring of the F-15 ACTIVE.
11. Attach the cutouts to the work sheet using the remaining brads by putting the brads through the center of gravity of each plane and then through the work sheet.
12. Label each view as showing either pitch or yaw and explain the purpose of pitch and yaw.

Assessment

Collect and review the work sheets.

Extension

Have students research pitch and yaw, and how they relate to flight.

Student Work Sheet Part 1

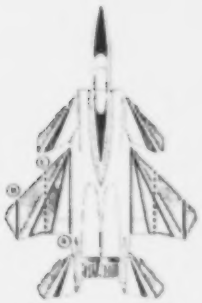
Name:_____

Date:_____

Finding Center of Gravity

Follow these steps to find the desired location for the center of gravity for the F-15 ACTIVE.

1. Measure the distance from the leading edge to the trailing edge of the wing:



A. Next to the fuselage _____

B. At the wing tip _____

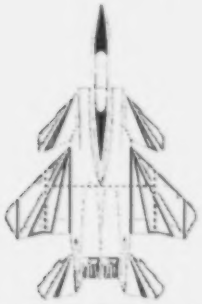
C. Add _____

D. Divide by 2 ÷ 2

E. Average wing chord _____

2. Use your ruler to locate the position on the wing that matches the length of the average wing chord you just calculated. Use the ruler to draw in the average wing chord. Make sure it is parallel to the fuselage.

3. Calculate the desired location of the center of gravity:



A. Average wing chord (from letter E) _____

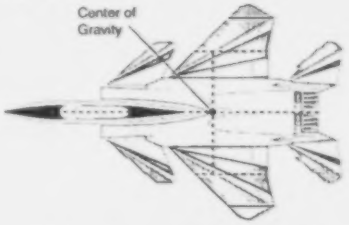
B. Find 25 percent of average wing chord x 0.25

C. Answer _____

4. Put a dot this distance back from the leading edge of the wings on both of your average wing chord marks. Use a straight edge to connect these two dots.

5. Fold your F-15 ACTIVE in half lengthwise to find the center axis.

6. Where the fold and the line connecting the 25 percent marks intersect is the location of the center of gravity for the F-15 ACTIVE. Put a large dot here.



Student Work Sheet Part 2

Name:_____

Date:_____

Center of Gravity, Pitch, and Yaw Work Sheet

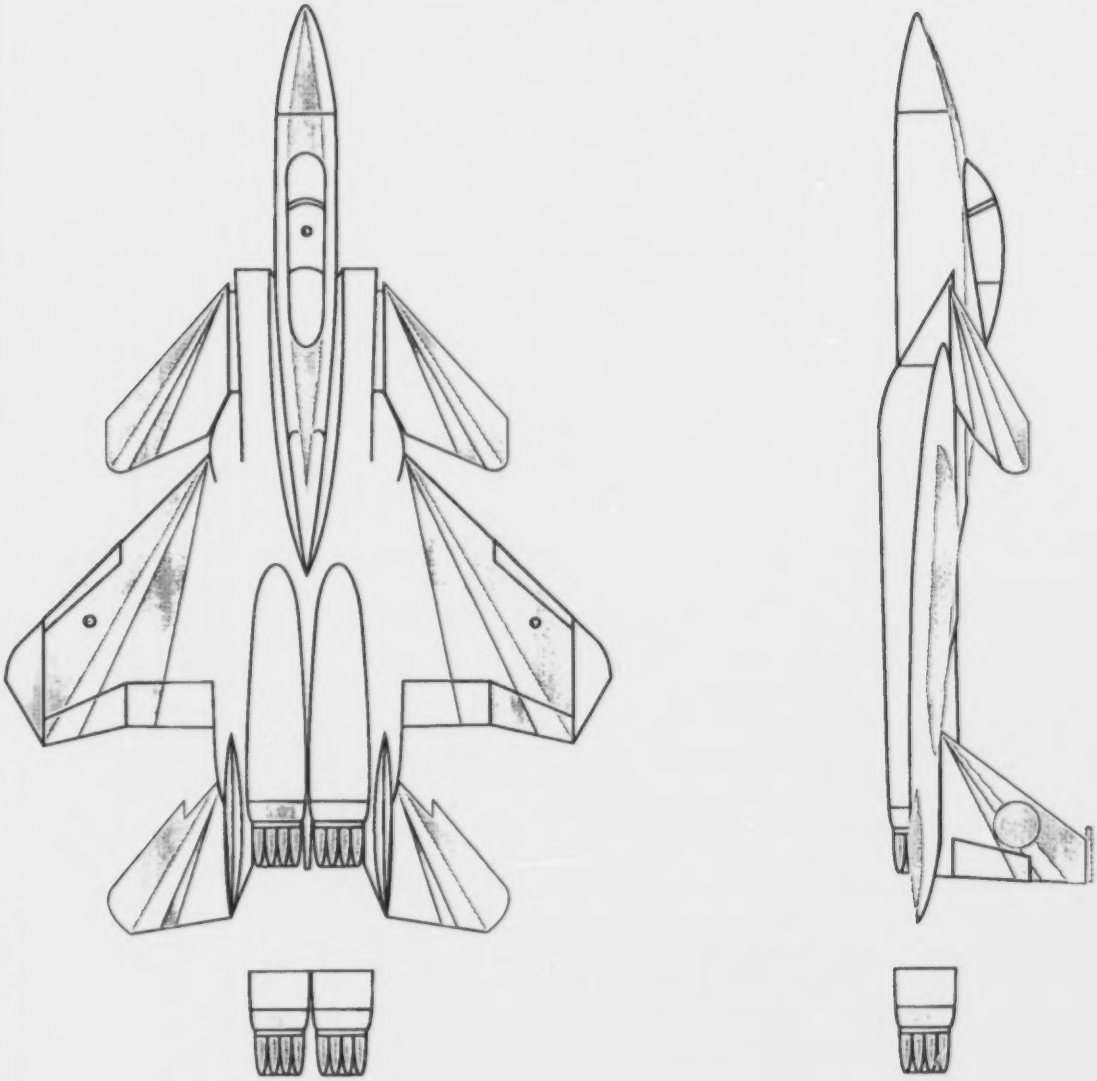
Directions

1. Mark the center of gravity on the top and side views of the F-15 ACTIVE.
2. Cut out the F-15 ACTIVE views and engines.
3. Attach the engines to the plane using one brad for each view. Put the brads through the dots on the engine pieces and the engine area on the plane. This will allow the engines to move and simulate the thrust vectoring of the F-15 ACTIVE.
4. Attach the cut-outs to the work sheet using the remaining brads by putting the brads through the center of gravity of each plane and then through the work sheet.
5. Label each view as showing either pitch or yaw and explain how pitch and yaw affect the flight of an aircraft.

(attach plane here)

(attach plane here)

F-15 ACTIVE TEMPLATE



Lesson 4: Fuel Efficiency
Grades 7 - 8

Objective
Graph variations in thrust/drag of F-15 ACTIVE when the tail sections are removed. Use the graph to draw conclusions about fuel efficiency.

Science Standards
Unifying Concepts and Processes
Change, Constancy, and Measurement
Evidence, Models, and Explanation
Science and Technology
Technological Design Abilities

Science Process Skills
Making Graphs
Controlling Variables

Mathematical Standards
Communicating
Reasoning
Computing and Estimating
Statistics

Management
This activity works best with students working individually, but giving assistance to each other. This is also best suited to students who have worked with formulas in the past. Allow 40-45 minutes to complete this activity. This activity is divided into two parts. In part 1 students use the formula for drag to calculate the difference in drag between an F-15 ACTIVE with the tail sections attached to the plane and again with the tail sections removed. In part 2 students will make conclusions about fuel efficiency with tails and without tails based on the graphs they constructed. This activity stresses precise calculations, graphing, analyzing graphical information, and drawing conclusions based on graphical information.

Background Information
One of the benefits of the thrust vectoring concept is the potential financial savings from increased fuel efficiency. Thrust vectoring may allow for the partial or complete removal of the vertical and horizontal tail. Doing this will reduce the weight of the aircraft and also reduce the amount of drag. When drag is reduced, the amount of thrust needed to fly the aircraft is also reduced, which reduces the amount of fuel required. Drag is calculated using the formula:

Drag = K x CD x V2

K = 1.06 (a constant calculated for flight at sea level. This number varies as wing area of the aircraft changes. Actual equation is included at the end for use if desired.)

CD = drag coefficient (assuming 0.02 with tails on, 0.01 without tails)

V = velocity of plane in feet per second

For straight and level flight under ideal conditions, when no wind is present and there is no acceleration or deceleration, thrust is equal to drag.

Description
Students will calculate the thrust/drag created by the F-15 ACTIVE with the vertical tails on and off. They will graph this information in a bar graph and make conclusions about the amount of fuel needed by both variations of the plane. The calculations can be done both at sea level and at 18,000 feet for additional comparisons.

Part 1

Materials and Tools

- Graph paper
- Colored pencils
- Straight edge
- Calculators

Procedures

1. Explain the concepts of thrust and drag to the students. Thrust is what pushes an object forward. Drag is what slows it down or pushes backwards.
2. Ask how thrust and drag have been demonstrated throughout the activities relating to the NASA F-15 ACTIVE project.
3. To this point these concepts have been observed subjectively. Now the students are going to learn how to calculate thrust and drag and make conclusions about fuel efficiency. NOTE: The number used for the drag coefficient is much larger for this activity than it is in actuality. This is so the students can draw conclusions based on the graph. The actual number is 2 percent of what is used here. Scientific calculations must be extremely precise and 2 percent is enough to make a difference to NASA engineers and scientists, it is simply too small for seventh and eighth grade students to notice a real difference. Precision in this activity is being sacrificed in order for the students to grasp more easily the concepts being presented.
4. Explain that in order for a plane to fly at a steady state, the amount of thrust put out by the engines must be equal to the amount of drag created by the plane (thrust=drag). Ask what they believe would happen if the amount of thrust was larger than the amount of drag. Then ask what would happen if the amount of thrust was less than the amount of drag.
5. Put this equation on the chalkboard or overhead:

   Drag = K x CD x V2 where:

   K = 1.06 (a constant calculated for flight at sea level. Actual equation is included at the end.)

   CD = drag coefficient

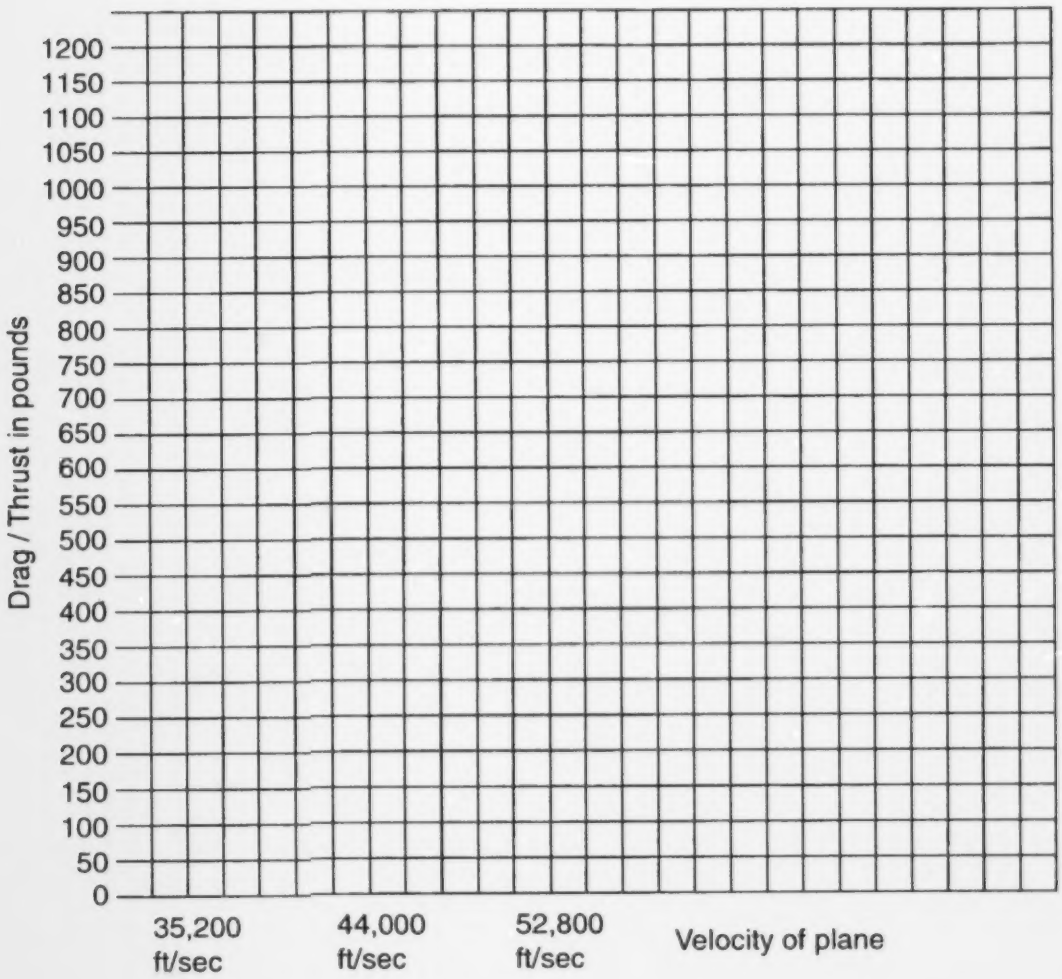
   V = velocity of plane in feet per second

   The drag coefficient of the F-15 ACTIVE is assumed to be 0.02 with tails on and 0.01 without tails. Work several examples with the students at various velocities and changing between the drag coefficient with tails and without tails so they understand the algebra involved.
6. Explain that they will only be focusing on straight and level flight. This means the amount of thrust is equal to the amount of drag. Therefore, the same equation for drag can be used to calculate thrust.
7. Have them calculate the thrust needed for three different velocities (for example: 35,200 ft/sec, 44,000 ft/sec, and 52,800 ft/sec). Make sure they calculate the thrust for both tails on (drag coefficient of 0.02) and tails off (drag coefficient of 0.01). The equation to convert from feet per second to miles per hour, and miles per hour to feet per second, has been included in the extension section.
8. Show them how to set up a set of axes for a bar graph using their straight edge to draw their lines. Vertical (y-axis) is thrust. Horizontal (x-axis) is for the labels for each bar. All three sets of double bar graphs may be done on one set of axes if desired. Indicate two colors for the bars should be used, one for tail on and the other for tails off. Also instruct them on setting the intervals for the vertical axis based on the calculations they made.

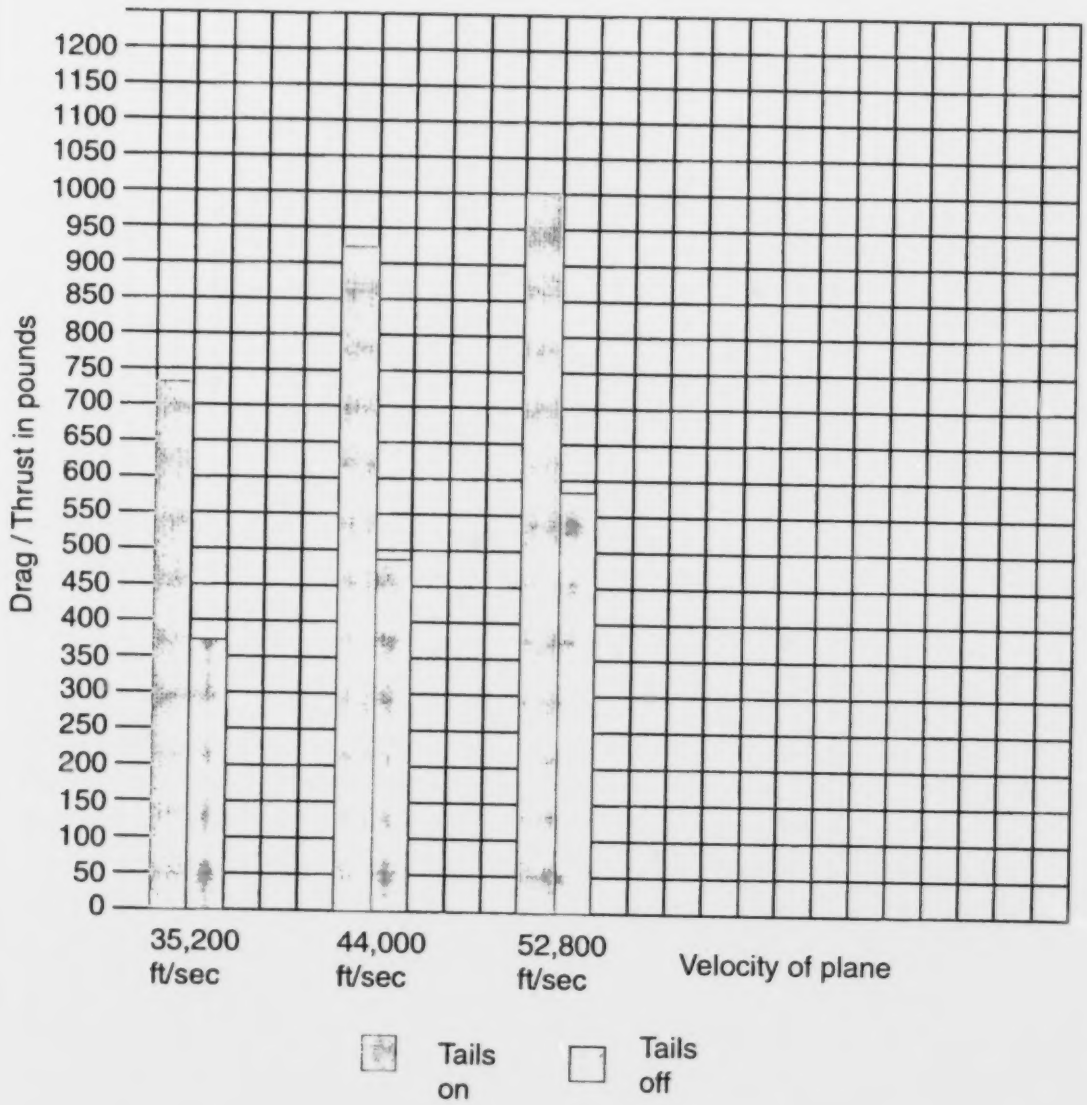
9. Draw the bar graphs using the straight edge. Make sure adequate space is allowed between each set of double bars. There should be one pair of bars for each of the different velocities. The students also should include a legend indicating which color was used for which condition.

Tail on	Tail off
CD = 0.02	CD = 0.01
T1=1.06 x 0.02 x 35,200 = 746.24 lbs	T1=1.06 x 0.01 x 35,200 = 373.12 lbs
T2=1.06 x 0.02 x 44,000 = 932.81 lbs	T2=1.06 x 0.01 x 44,000 = 466.41 lbs
T3=1.06 x 0.02 x 52,800 = 1119.36 lbs	T3=1.06 x 0.01 x 52,800 = 559.68 lbs

Bar Graph


Drag / Thrust in pounds
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
35,200 ft/sec
44,000 ft/sec
52,800 ft/sec
Velocity of plane

Bar Graph Answers



Part 2

Materials and Tools

- Graph from Part 1
- One copy of Student Work Sheet per student (see page 63)

Assessment

Conduct a class discussion where students share their conclusions about thrust vectoring and fuel efficiency. Collect and review students' written conclusions.

Discussion Questions

Have students use their graphs to answer the following questions:

1. Which situation, with tails on or without tails, needs the most thrust?
2. Which situation creates the least amount of drag?
3. How would an increase in the thrust affect the amount of fuel needed?
4. Which situation would be the most fuel efficient? Least fuel efficient?
5. Which situation would need thrust vectoring to ensure controlled flight?
6. What conclusions can be drawn regarding the fuel efficiency of thrust vectoring based on your graph and the answers to the previous questions?

Extensions

1. Convert velocity, "V", from feet per second to miles per hour:

$$V \times \frac{60 \text{ seconds}}{1 \text{ hour}} \times \frac{1 \text{ mile}}{5280 \text{ feet}}$$

2. Convert velocity, "V", from miles per hour to feet per second:

$$V \times \frac{1 \text{ hour}}{60 \text{ seconds}} \times \frac{5280 \text{ feet}}{1 \text{ mile}}$$

Student Work Sheet
Name:_____
Date:_____

Fuel Efficiency Work Sheet

Use your graph to answer the following questions about the fuel efficiency of thrust vectoring.

1. Which situation, with tail or without tail, requires the most thrust?

_____

2. Which situation, with tail or without tail, creates the least amount of drag?

_____

3. How would an increase in the thrust affect the amount of fuel needed?

_____

_____

4. Which situation would be the most fuel efficient? Least fuel efficient?

_____

_____

5. In which situation, with tail or without tail, would thrust vectoring be used to ensure controlled flight? (Hint: Think back to the experiments done in lesson 4.)

_____

_____

6. What conclusions can be drawn regarding the fuel efficiency of thrust vectoring based on your graph and the answers to the previous questions?

_____

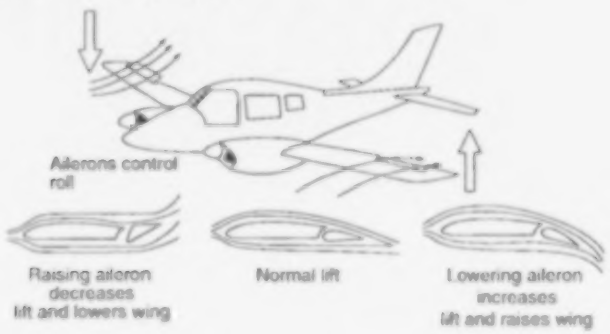
_____

Glossary

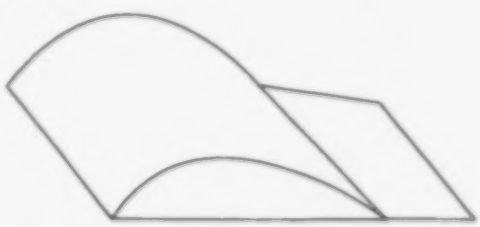
Aeroelastic Divergence: Aeroelasticity is the science that studies forces causing structural bending and flexing of aircraft components such as wings. When a forward-swept wing produces lift, structural bending causes the forward edge of the wing to increase incidence (it bends upward). This in turn further increases the aerodynamic lift until at some speed (or value of lift) the aerodynamic forces overcome the structural restoring forces of the wing. This is called aeroelastic divergence and causes the wing to bend up until it breaks.

Afterburner: On some jet engines, a tailpipe section aft of the turbine where additional thrust is produced. Afterburner operation is not continuous but can be selected by the pilot, normally by moving the throttle lever forward through a detent to the afterburner position. Additional fuel is then injected into the hot exhaust gases and combustion significantly increases the thrust compared to that of the basic engine. Unfortunately, fuel consumption is even further increased. Also "reheat" [UK], "augmented thrust," or "max thrust."

Aileron: A movable section on a wing used for controlling the roll attitude of the airplane. Ailerons are normally located on the outboard trailing edges of each wing and are interconnected so as to move in opposite directions. Downward aileron movement on one wing increases that wing's lift while a corresponding upward aileron movement on the opposite wing decreases lift; the unbalanced forces cause a roll towards the wing with upward aileron deflection. Ailerons are controlled by the pilot's control stick or wheel, which is moved in the direction of desired roll. (From "aleron," French for "wing tip.")


Ailerons control roll
Raising aileron decreases lift and lowers wing
Normal lift
Lowering aileron increases lift and raises wing

Airfoil: A solid surface designed to move through air and obtain a useful force called lift. Examples are wings, sails, propeller blades, and helicopter rotor blades. In the study of aerodynamics, "airfoil" usually refers to the cross-sectional shape obtained by the intersection of the wing with a perpendicular plane.



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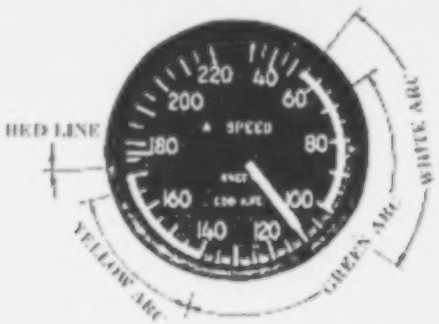
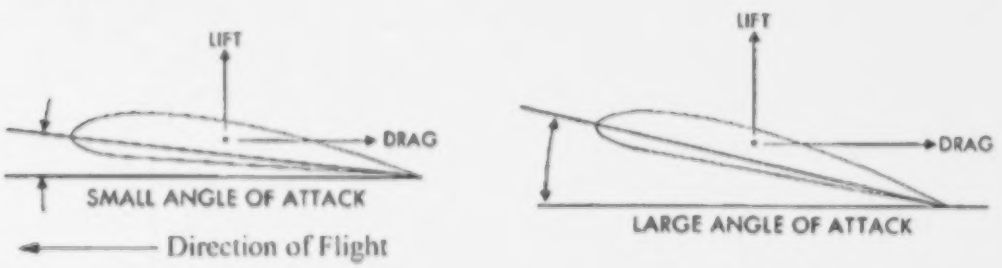
Airspeed: The speed of an airplane relative to the surrounding air ("groundspeed" would be the airplane's speed relative to the ground; the two would be equal in the absence of wind). Airspeed is usually measured by a "Pitot-static system," which reacts to air pressure caused by movement of the airplane through the air.

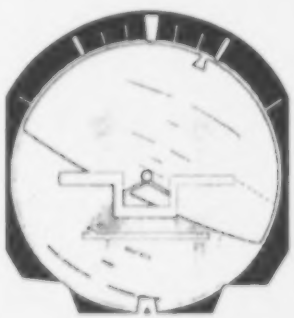
Airspeed Indicator: An instrument in the pilot's cockpit giving continuous indication of airspeed. Usually, airspeed indicators show the speed in units of knots (1 knot = 1 nautical mile per hour where 1 nm = 6000 feet). However, many of the smaller airplanes have airspeed indicators calibrated in mph (1 mph = 1 statute mile per hour where 1 sm = 5280 feet).



Angle-of-Attack (AOA, alpha, a): The angle of incidence of the airplane's wing (or other reference) with the airflow direction. The airflow direction relative to the airplane is often termed the "relative wind."



Attitude: An airplane's pitch, roll, and/or yaw angle relative to the Earth's horizon or another reference. Attitude is displayed to the pilot on an instrument called an "attitude indicator."



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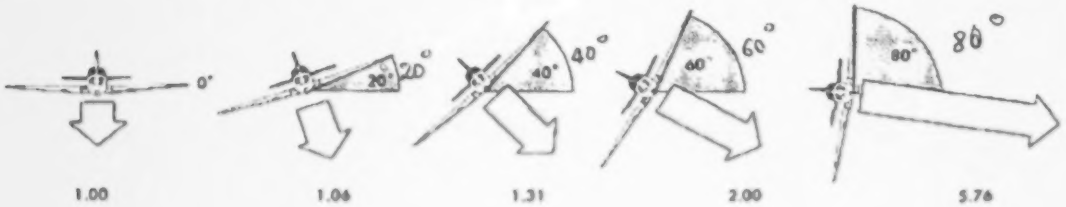
Bank Angle: Airplane's angle of bank relative to the Earth's horizon (see **roll**).



Bleed Air: Air under pressure that is bled from a jet engine for purposes other than producing thrust. These uses include cockpit or cabin pressurization and air conditioning or, in the case of the Harrier, air to power the "puffer jet" reaction control system.

Canard: A horizontal control surface mounted in front of the wing. Also, "foreplane."

Control (or Command) Augmentation System (CAS): An electrical circuit between the pilot's controller (stick, wheel, sidestick) and the control surface, which essentially boosts the pilot's initial control force and makes flying the airplane easier and more precise; "power steering." Sensors in the CAS circuit provide feedback signals (typically load factor, pitch rate, or roll rate) to a computer, which compares them to the pilot command signal to make the airplane respond as desired. In this manner, aircraft response is consistent over most of the flight envelope, and unwanted motions are heavily damped.

Center of Gravity (CG, c.g.): Point through which the force of gravity acts and about which the airplane is balanced. An airplane's longitudinal, lateral, and vertical axes intersect at the c.g. The location of the c.g. is normally given in inches from a datum or expressed in terms of the wing's mean aerodynamic chord (%MAC).

Compressibility: Phenomenon of air moving over a curved aircraft surface at speeds close to local sonic speed, where air can no longer be considered as incompressible (as it is assumed to be for most subsonic aerodynamics applications). Effects include the appearance of shockwaves, rapid increase in drag, rearward shift of the lift forces, and, for improperly designed aircraft, stability and control problems.

Control Laws: The sequence of calculations an electronic flight control system uses to control aircraft response to pilot inputs and external disturbances such as wind gusts.

Damper: An electrical circuit in a flight control system that senses uncommanded motion and moves a control surface to stop unwanted oscillations. Typically, pitch, roll, and/or yaw dampers are used. (See **Stability Augmentation System**.)

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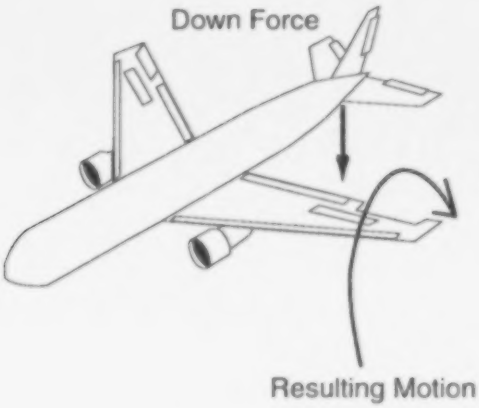
Drag: Retarding force acting upon an airplane parallel to the direction of motion. "Parasite drag" is caused by the friction of the air moving over the airplane. The other basic type of drag is related to the wing's production of lift and is called "induced drag." Induced drag is affected by the wing's shape, the angle at which the air strikes the wing, and the speed and density of the airflow.

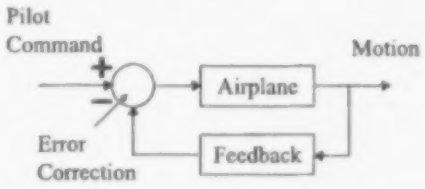


Dynamic Stability: An airplane's response over time to a disturbance from the trim condition (a state of equilibrium). The response may diverge from the trim condition, converge back to trim, or oscillate about trim. An oscillatory response may continue to increase in amplitude, stay about the same, or decrease in amplitude ("damp out").

Elevator: A movable control surface hinged to the trailing edge of a horizontal stabilizer that is connected to the pilot's controls (stick, wheel, sidestick). Aft motion of the pilot's control causes the elevator to deflect and produce a nose-up pitch response; forward control motion causes a nose-down pitch response.

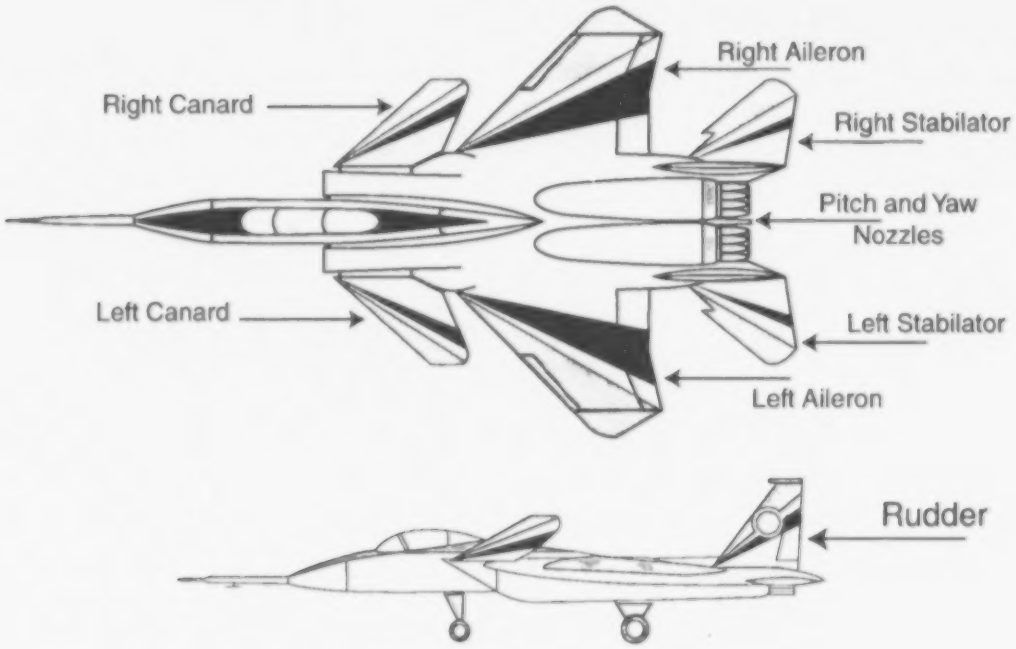
Elevons: A hinged control surface on the trailing edge of a wing that is connected to the pilot's controls combining the functions of elevators and ailerons. Elevons are often used on delta-wing aircraft.

Feedback Control System: Circuit of a flight control system that regulates aircraft response through feedback compensation techniques. The pilot's control input becomes the system's command; resultant aircraft motions are measured, transformed into electrical signals, and then conditioned and amplified for summing with the input command. This forms a closed loop, illustrated below. The error between the output and input signal becomes an electrical command to the flight control surfaces until output equals input.

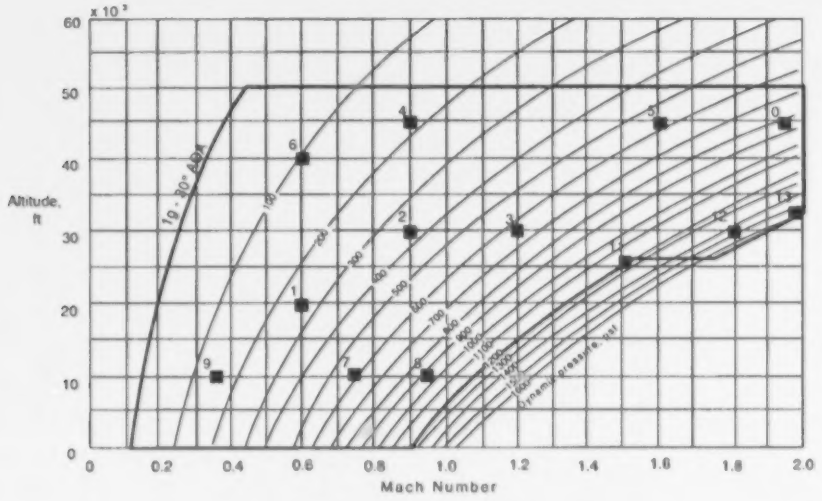


Flight Controls: Devices the pilot uses to steer and control the trajectory of an airplane; also refers to the external surfaces responding to the pilot's flight control movements or inputs. The pilot's controls, the external surfaces, and all mechanical and electrical linkages, computers, and sensors in between make up the flight control system. Pilot's controls usually include a center stick, control wheel, or sidestick; flap lever; speed brake handle or actuation button; and nozzle angle position lever in the case of the Harrier.

Flight Control Surfaces (or Effectors): The external surfaces that respond to pilot inputs to control the airplane's trajectory. Primary surfaces produce direct response in pitch, roll, and yaw. These include elevators, stabilators, canards, elevons, tailerons, ailerons, rudders, and thrust vectoring nozzles. Secondary flight control surfaces augment the primary surfaces by modifying the lift and drag characteristics of the wings and airplane. These include wing flaps (usually on the trailing edge but sometimes used on the leading edge), wing slats, spoilers, and speed brakes (UK = "air brakes"). The recent terminology for primary flight controls is "flight control effectors," as the effector may not be a conventional control surface. For example, NASA's F-15 ACTIVE research aircraft is said to have nine flight control *effectors*: left and right canards, left and right ailerons, rudder (the two rudders move together and are treated as one effector), left and right stabilators, and pitch or yaw TV (thrust vectoring).



Flight Envelope: The boundaries of speed, Mach, altitude, load factor, and angle-of-attack within which a particular airplane design can sustain flight. A typical flight envelope is presented as a two-dimensional plot with altitude on the y-axis and speed/Mach on the x-axis.



ACTIVE envelope

Fly-By-Wire: The generally accepted terminology when the pilot's control commands are processed by a computer and sent to the flight control surface actuators with electrical signals (or fiber-optic signals, sometimes called "fly-by-light") rather than mechanical linkage. NOTE: "power-by-wire" is a recent term for flight control surface actuators that are electrically powered, as opposed to the conventional hydraulic-powered actuator.

g Loading (load factor, g, n, Nz): The increase in apparent weight of the pilot and aircraft when an airplane is maneuvered in flight, caused by inertia forces. Load factors are measured in reference to the vertical (Z) axis by accelerometers and expressed in "g" units. In level flight with no turning, the load factor is at 1g and the load on the structure is equal to the weight of the structure. If the aircraft turns or pulls up at 2 gs, the load on the structure and pilot is twice their weight. Since wing lift must be increased to effect a turn or other maneuver, it can be shown that the load factor equals the ratio of lift to weight: n = L/W.

Head-Up Display or Heads-Up Display

To improve flight safety and reduce pilot workload in high-performance aircraft, critical parameters such as aircraft attitude, altitude, airspeed, and navigation information are viewed directly by the pilot via a plasma display embedded into the windshield or canopy of the aircraft. This reduces the need for the pilot to divert his attention to the instrument panel inside the cockpit, especially for those parameters he views directly on the windshield.

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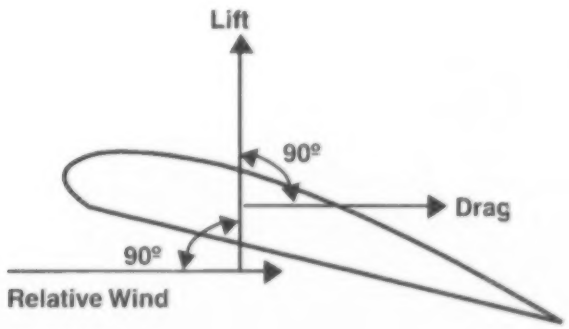
Horizontal Stabilizer: A horizontal airfoil at the rear of an airplane providing stability in pitch. The stabilizer may be fixed or have a small angular adjustment for trim only. Elevators may be mounted on the back. In some designs, especially supersonic airplanes, the entire stabilizer is pivoted and moves for pitch control. Also, tailplane.

Lift: The useful force produced by a wing as air flows over it. Air travels faster over the curved upper surface than along the bottom, which creates lower pressure on the top and higher pressure on the bottom. The pressure differential creates a "vacuum" suction on the upper surface, tending to lift the wing. The pressure differential can be represented by a single force acting at a location called the "center of pressure" and perpendicular to the relative wind. The amount of lift is affected by the shape of the wing, the angle at which the wind strikes the wing, and the speed and density of the airflow.

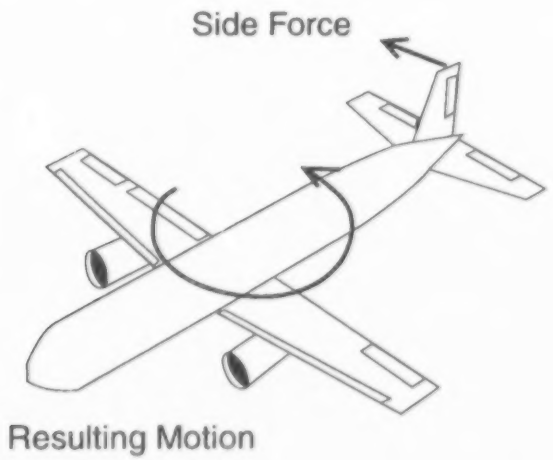


Mach Number: Ratio of aircraft's airspeed to the speed of sound: M= V/a where *V* is true airspeed and *a* is the speed of sound which varies with air temperature. At Mach 2, an aircraft is traveling at twice the speed of sound. The term is named after Ernst Mach (1838-1916), an Austrian physicist.

Maneuverability: The ability of an aircraft, as commanded by its pilot, to change trajectory. A pilot must be able to hold an airplane in a maneuver, and the designer has to provide adequate flight control effectors appropriate to the role of the aircraft. Maneuverability is opposed by stability; that is, the less stable an airplane, the more maneuverable it is. However, some degree of stability is required in order for the pilot to maintain the desired trajectory.

Nozzles: The aft section of a jet engine tailpipe through which the exhaust gases escape. Usually, the nozzle is designed with interleaved metal sections (nozzle leaves), which allow the nozzle exit area to be varied. If the nozzle exit area is decreased, the exhaust velocity is increased by the relationship $V_2 = (A_1/A_2)\, V_1$. A nozzle controller continuously varies the exit area to provide optimum exhaust gas velocity and internal tail pipe temperature. Recent nozzle design provides the ability to vary the nozzle and exhaust gas angular direction to provide thrust vectoring.

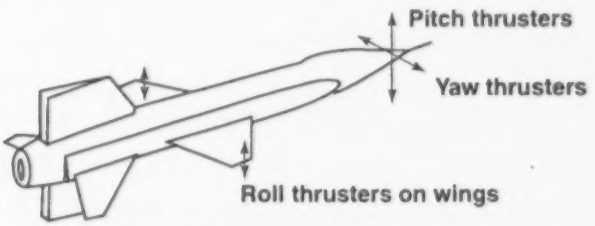
Pitch, Pitch Attitude: Angular rotation about the airplane's lateral (Y) axis, usually termed "nose up" or "nose down." The angle between the airplane's longitudinal (X) axis and the Earth's horizon is called pitch attitude. Pitch is produced by the elevators (or canards, or pitch thrust vectoring).



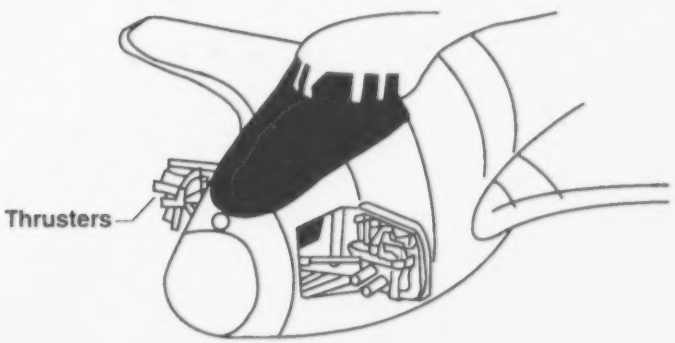
Positive Static Stability: The level of static stability of an airplane is determined by the relationship or location of the aerodynamic center of pressure (ac) with respect to the airplane's center of gravity (cg). Typically the more forward the center of gravity from the aerodynamic center, the more positive static stability an airplane will have. This means that following application and removal of a disturbance, the airplane will return to its initial undisturbed equilibrium position relatively quickly.

Quadraplex: To provide security in the event of certain critical complex airplane system failures, such as a flight control computer, four (*quadraplex*) computers are utilized to perform similar simultaneous functions. Each computer checks on the others to verify that they all agree by comparing output commands. If one computer or system command output is found to differ, it can then be deactivated or ignored and the others will continue their normal function, thus avoiding the possibility of a catastrophic situation.

Reaction Control System: In the absence of atmospheric aerodynamic pressure acting on a space plane's control surfaces (elevator, ailerons, or rudder), to change its attitude or position with respect to another object, such as the Earth, another means must be employed. Such a system must be utilized in space where no aerodynamic force can be produced. In the vacuum of space, small on/off rocket motors (thrusters) must be used by a spacecraft to produce the force to change vehicle attitude or position. The jet thrust of small reaction engines (thrusters) is developed by ejecting a substance, such as a stream of gases, from burned fuel (see diagram below). This type of *reaction control system* (RCS) is controlled by a pilot or computer and is usually either on or off; variable levels of thrust are usually not available. The density of the atmosphere decreases as a function of altitude. Approximately 50 percent of the Earth's atmosphere is below 18,000 feet (5,486 m). As altitude increases the number of molecules or mass per unit volume



(a) X-15 reaction controls



(b) Space Shuttle reaction controls

Examples of reaction controls

decreases, resulting in a decrease in atmospheric pressure. As altitude increases, aerodynamic pressure on aircraft control surfaces decreases to a point where reaction control thrusters must be blended with aerodynamic control to maintain adequate control. As altitude increases further, aerodynamic controls must be phased out and reaction controls phased in. Once out of the atmosphere, reaction control thrusters are then the sole means of orienting or maneuvering the vehicle. In the return to Earth, the control system must phase out the thrusters and phase in aerodynamic control.

Relaxed Static Stability: As the location of the center of gravity (c.g.) with respect to the airplane's aerodynamic center of pressure (a.c.) is decreased, as the case when the c.g. is allowed to move aft, the airplane's static stability will be *relaxed* or decreased. This means that following application and removal of a disturbance, the airplane will return to its initial undisturbed equilibrium position less quickly. If the c.g. is allowed to move aft of the a.c., the airplane will become unstable (*negative static stability*). This is the situation in which, when disturbed from a condition of equilibrium by some force, the airplane will not return to its initial undisturbed position or attitude following removal of the disturbance force, but will continue to diverge from that position.

Roll, Roll Attitude, Bank Angle: Angular rotation about the airplane's longitudinal (X) axis, usually called "right/left roll" or "right/left bank." The angle between the aircraft's vertical (Z) axis and the Earth's vertical is the roll attitude or bank angle. Roll is produced by the ailerons (or spoilers, tailerons, or elevons).

Roll Coupling: "Coupling" is what happens when a motion about one axis causes a motion about another axis. Roll coupling is a divergence in pitch or yaw during rolling maneuvers. It is caused by a complicated interaction of inertial and aerodynamic properties and can lead to loss of control or structural failure. Many high-performance aircraft with fly-by-wire flight control systems incorporate a roll rate limiter to avoid roll coupling.

Rudder: A movable flight control surface hinged to the back of the vertical stabilizer, providing yaw control. The rudder is connected to a set of pedals operated by the pilot's feet; the right pedal moves (yaws) the nose to the right, and left pedal moves the nose left. This yawing motion pivots the airplane about the vertical (Z) axis. Since the directional stability of an airplane is necessarily very high, full rudder deflection normally produces small angular displacements compared to pitch or roll capability, perhaps 15° or less yaw angle at normal cruise speed.

Shockwave: The air pressure waves ahead of a supersonic airplane bunch, because the speed of propagation of the pressure waves is finite (the speed of sound), and form a surface of discontinuity where the flow changes from subsonic to supersonic. The shockwave forms a three-dimensional conical surface, sometimes called a Mach cone. Shockwaves cause a change in the airflow pressure patterns around an aircraft. This will ultimately change its maneuverability, stability, and control characteristics.

Sideslip: When an airplane is not flying straight but has an angle between the fuselage and the direction of motion (flight path, or relative wind), it is said to be in a "sideslip." This causes additional drag.

Spin: A dangerous maneuver in which the aircraft has stalled and entered a sustained yawing rotation about the vertical axis and a near vertical descent.

Spoiler: A small control surface on the top of a wing that decreases (spoils) the wing's lift by deflecting the airflow over the wing. This drag is used to augment roll control when spoilers on one wing only (the down-going wing) deflect or to provide quick airspeed reduction when spoilers on both wings deflect. The latter function is called a speed brake (UK: "air brake"), which the pilot controls by a speed brake extension lever. These may also be extended after landing to aid deceleration and reduce landing distance.

Stability: The property of a body, as an aircraft or rocket, to maintain its attitude or to resist displacement, and if displaced, to develop forces and moments tending to restore the orginal condition.

Stability Augmentation System (SAS): An auxiliary system to the basic manual vehicle control system, whereby response of the control surfaces to inputs by the pilot can be adjusted to give a preselected vehicle response by selection of certain fixed gains in a standard feedback loop on control-surface output.

Stabilator: Single-piece horizontal tail control surface used as primary pitch control, especially on supersonic aircraft where shockwaves might reduce the effectiveness of an elevator type control. Also "stab" and "slab."

Static Stability: The tendency of an airplane (or body), when disturbed from a undisturbed position or attitude, following removal of the disturbance force. Airplanes possess a delicate and important balance between aerodynamic and gravitational forces. A more stable airplane is more difficult to move using controls, so if ease of maneuverability is desired, then decreasing or relaxing its stability will achieve this objective.

Stall: A flight condition that occurs when the angle-of-attack becomes so high that the air flowing over the top of the wing no longer flows smoothly, but breaks away (stalls), causing a rapid loss of lift. The associated angle-of-attack is called the "stall angle-of-attack" and is always the same angle for a given wing shape.

Stick: A control *stick* is a pilot cockpit control and is a primary flight control device (a control wheel may also be used in larger airplanes). A pull or push on the stick controls the airplane pitch attitude. Push results in nose down and pull results in nose up. Left stick or wheel deflection rolls the airplane left, and right stick rolls to the right.

Swept Wing: The term for wings that are inclined towards the back of the airplane. Also called sweepback, and the angle between the longitudinal axis and the wing leading edge (or other reference such as the quarter-chord line) is the "sweepback angle."

Taileron: A stabilator design where the left and right halves can move in unison for pitch control or differentially to produce roll; may produce both pitch and roll simultaneously. Also, differential tail.

Tricycle Landing Gear: Landing gear, or wheels of an airplane, consisting of two main wheels and a nose wheel that provide support for the airplane while on the ground.

Thrust: The pushing or pulling force of an aircraft engine that gives it the forward motion through the air to create lift. In a jet engine, air flows in through the front of the engine and is mixed with fuel and compressed. A spark plug makes the fuel mixture burn, expand, and rush out through the exhaust nozzle at the back of the engine to make the airplane go forward.

Thrust Reverse (Reverse Thrust): The simplest and most general use of thrust vectoring is *reverse thrust*. This is typically used on large jet airliners to a stop in short distances. Propeller blades may also be reversed on some airplanes to achieve the same objective. Reverse thrust engines are equipped with a mechanism that turns the normal rearward thrust force 180° to a near-forward direction.

Thrust Vectoring: Thrust is a force and as such has both magnitude and direction, which makes it a *vector* quantity. Normally, the thrust of an airplane cannot be changed except by turning the vehicle. If, however, some mechanism is provided to turn, deflect, or rotate an airplane's thrust vector, with respect to the vehicle, it is capable of *thrust vectoring*. This type of system is used to enhance maneuvering.

Trim: That state of airplane flight where all forces and moments are in balance and little, if any, control is required to maintain the condition.

Triplex: Similar to a quadraplex system except the number of complex systems is only three (triplex) rather than four.

Variable Geometry: Some highly specialized airplanes such as the B-1, F-111, and F-14 have the ability to change wing sweep in flight. These are referred to as variable geometry airplanes due to their ability to change shape as flight conditions dictate. Typically they have low sweep (wing forward) at low speed and high sweep (wing aft) at high speed.

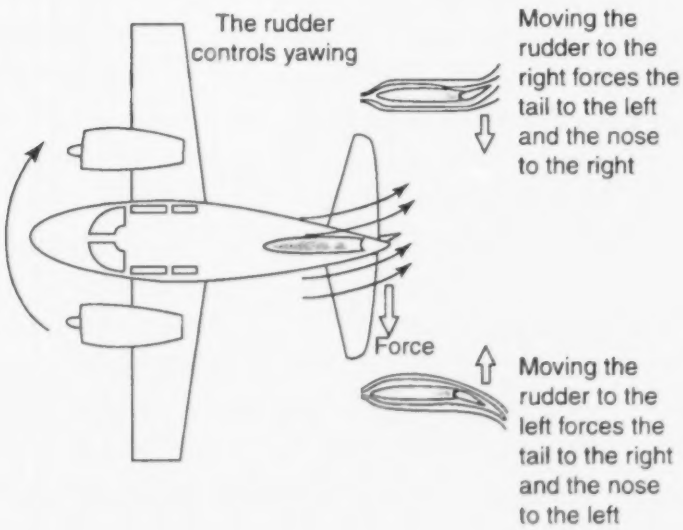
Variable Stability: Some experimental airplanes have complex computer systems installed so that their stability and or flight characteristics can be artificially altered in flight based on some predetermined plan. These systems allow the simulation of increased or reduced (*variable*) stability or duplicating the flight characteristics of other airplanes for study or pilot familiarization purposes.

Vertical Fin (Vertical Stabilizer): A fixed vertical airfoil surface usually at the rear of an airplane that provides directional stability. Rudder controls are hinged to the back of the vertical stabilizer. In some supersonic designs, the entire vertical stabilizer can move, similar to a horizontal stabilator. Also, "fin."

Wing: The airfoil surface that produces the main source of lift for an airplane. The front of a wing is termed the leading edge while the back is called the trailing edge. The intersection of the wing and fuselage is called the wing root.

Wing Warping: During the development of the airplane the Wright brothers determined that the ability to control or steer and airplane was as important as the wing's ability to generate lift. The construction of the first airplanes was of wood, wire, and linen fabric. The Wright brothers determined that if they pulled down and twisted (warped) the outboard trailing edge of a wing, the airplane would roll or bank in the opposite direction. That is, the right wing trailing edge down the airplane would roll left, and vice versa. This method literally distorted or warped the wing (hence the term wing warping). Without the ability to bank an airplane, it is virtually impossible to accomplish a turn. Modern airplanes use ailerons to accomplish banked turns and roll maneuvering, and the wings cannot typically be warped.

Yaw: Angular rotation about an airplane's vertical (Z) axis. Yaw is produced by the rudder. Undesired yaw may also be produced by the use of ailerons or other roll controls for banking. This is called "adverse yaw" if the nose moves opposite the direction of roll and "proverse yaw" when the nose moves in the same direction. This undesired yaw is an example of coupling (motion about one axis causing motion about another axis) and is due to the lift vectors of the up-going and down-going wing being inclined at different angles during a roll. Therefore, a pilot of a conventional airplane must often use the rudder simultaneously with the ailerons to prevent undesired yaw. This is often termed coordinating a turn.


The rudder controls yawing
Moving the rudder to the right forces the tail to the left and the nose to the right
Force
Moving the rudder to the left forces the tail to the right and the nose to the left

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